ALTERNATING-CURRENT RAILWAYS

(PART 1)

THREE-PHASE RAILWAYS

CHARACTERISTICS OF THREE-PHASE MOTOR

DEVELOPMENT OF ALTERNATING-CURRENT RAILWAYS

1. Introductory.—The application of electric propulsion to long railway lines has brought forth conditions that require a more economical and efficient system of current distribution than is possible with direct current at the usual voltage of 650 or less. The cost of copper conductors required to transmit very large currents over long distances, with a reasonable loss of power in the transmission system, prohibits their use. This has led to the development of the high-tension alternating-current generating station in conjunction with substations to convert the alternating current to direct current, from which direct current at a pressure of about 600 volts is supplied to the railway lines. The substation machinery is expensive, and a number of skilled attendants are necessary in each station. As the size of the train equipments increased, the current on the low-tension direct-current circuits became excessive, and the safe limit of the carrying capacity of the trolley wire was exceeded. The third-rail system is extensively used and a large current may be carried by the conductor rail, but it is not advisable to place the

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supply conductors so near the ground when alternating current at high voltage is employed.

2. If a high-voltage alternating current is supplied to the trolley line and then utilized for propelling trains by means of alternating-current motors, the trolley wire may be of moderate size, even though its length is great and the train load heavy. With alternating current in the transmission lines from the generating station to the substations and in the trolley lines, the substations need contain only static transformers and auxiliary switching apparatus; that is, no moving machinery is necessary. The substation equipment is then of comparatively low cost, and little, if any, attendance, except regular inspection, is required.

3. **General Construction.**—In principle, the three-phase railway motor is similar to the ordinary stationary three-phase motor, but structurally there are many points of difference. The railway motor is subject to severe vibration; consequently, the air gap is made somewhat longer and the shaft stiffer than for a stationary motor, and the bearings are made extra large. The air gap cannot be greatly increased, because of the reduction in power factor and overload capacity which results. The percentage of space allowed for insulation is also extra large, to allow for excessive mechanical as well as electrical stresses. For considerations of space and weight, the magnetic and current densities in traction motors are generally higher than those in motors in stationary working. The slip is therefore usually higher in traction motors. There are also various other changes due to the special methods of working the motors.

4. **Use of High Voltage.**—The voltage which can be used directly across the stator windings of three-phase traction motors is limited only by the insulation of the windings. The voltage on the trolley wires is limited by the possibility of sparklessly collecting the current from the wires. In practice, pressures of 3,000 volts, 6,600 volts, and even 10,000 volts between the lines have been successfully employed, the motors and controlling apparatus operating satisfactorily, and the current being collected

by means of specially designed bow collectors without any harmful sparking, even at very high speeds. It is, of course, possible to use static transformers to reduce the voltage for the motors; this increases the weight and cost of the locomotive, and, for pressures up to 10,000 volts, transformers have not been found to be necessary.

5. **Choice of Frequency.**—The frequency at which current is supplied has a considerable effect on the drop occurring in the trolley wire and track rails. The higher the frequency, the greater will be the drop with a given current; the drop depends also on the shape and material of the conductor as well as on its sectional area and length, and is greatest with iron conductors. Therefore, if the steel track rails are used as one of the conductors, the voltage drop in them must be carefully considered. Some years ago twenty-five cycles per second was considered a very low frequency, but the tendency is now to make fifteen cycles per second the standard for railway working. The Simplon Tunnel Railway and the Valtellina Railway work with a supply at sixteen and fifteen cycles per second, respectively.

BEHAVIOUR AS ASYNCHRONOUS MOTOR

6. **Speed.**—The induction motor is the type used on three-phase railways, as it is the only type of polyphase motor which is capable of giving the large starting torque necessary for traction work. The speed of an induction motor is practically constant at all loads. Under working conditions, the maximum variation for a traction motor does not exceed 8 per cent. of the synchronous speed, whether the train is running up a gradient, on the level, or down a gradient. The synchronous speed of an induction motor is the speed at which the magnetic poles rotate round the stator core. The rotor runs at a speed slightly less than the synchronous speed when the motor is delivering mechanical power to the shaft. The amount that the speed of the rotor differs from the synchronous speed is called the slip. In Fig. 1, curve *a* shows that the speed of a certain 64-horsepower motor varies from nearly 600 revolutions per minute at no load to 567 revolutions per minute at full load.

7. Power Factor.—The induction motor has a power factor which is invariably less than unity, whether the speed is below synchronism, and the machine is acting as a motor, or above synchronism, and the machine is acting as a generator. At small loads the power factor is low, and gradually increases with the load up to a certain point, after which it falls off again. The point at which the maximum power factor occurs varies with

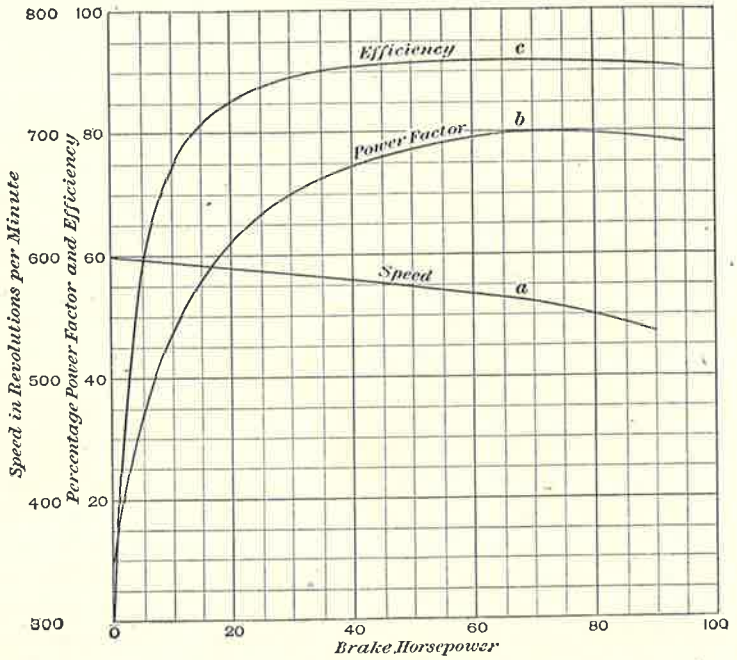

FIG. 1

the design of the motor from $\frac{3}{4}$ to $1\frac{1}{4}$ full load. In Fig. 1, curve *b* shows that the power factor for a certain 64-horsepower motor is slightly less than 80 per cent. at full load and increases until the load exceeds 76 horsepower, after which it falls.

8. Torque and Efficiency.—The motor has a definite maximum torque, so that if the resistance to motion is greater than a certain value the motor will stop. This maximum depends

primarily on the design and magnitude of the motor, and secondarily on the voltage and frequency of the supply. Any fall in the voltage or any rise in the frequency will reduce the maximum available torque which the motor can exert.

The speed corresponding to any given torque depends on the resistance of the secondary windings; if arrangements are made, by means of slip-rings and external resistances, to vary the resistance of the secondary windings, the speed of the motor can be regulated to any value between the maximum and zero. Such regulation involves, however, electrical losses in the resistances, and reduces the efficiency in approximately the same ratio that the speed is reduced.

The efficiency of the motor is usually at its maximum somewhere near full load, but does not vary to any great extent between $\frac{3}{4}$ and $1\frac{1}{4}$ load. In the particular case of a 64-horsepower motor, curve *c*, Fig. 1, shows a maximum efficiency of 92 per cent. and but small variation for a wide range of loads.

BEHAVIOUR AS ASYNCHRONOUS GENERATOR

9. Advantage of Regeneration.—It has already been pointed out that the three-phase induction motor is essentially a constant-speed machine, and tends to run always within a very small margin of synchronous speed. Below this speed the motor is making an effort to accelerate, and above this speed, to retard. Acceleration involves the supply of energy to the accelerated body; retardation involves the extraction of energy from the retarded mass. If a car fitted with three-phase induction motors is running down a gradient, the speed of the motors may be brought above synchronous speed, in which case they will act as generators, supplying electrical energy to the line and absorbing mechanical energy from the driving wheels. It was found that the trains on the Swiss mountain railways could be kept in check by the induction motors alone acting as generators, thus making the use of mechanical brakes unnecessary. The system of returning energy to the line by making the car drive the motors as generators when descending gradients is called a **recuperative,** or **regenerative, system.**

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10. On the mountain railways previously mentioned the regenerated energy cannot always be usefully applied, because there are usually only two trains, one of which may not always be ascending when the other is descending.

In systems where there are a considerable number of trains running, the recuperative, or regenerative, system has been used with great success and economy. Not only do the descending trains generate energy, which goes to help other trains that may be ascending, but also, when stopping, part of the energy that would otherwise be wasted in wearing away the wheels and brake blocks is saved.

11. The regenerative property of the three-phase motor sharply differentiates it from motors working with single-phase alternating current and from ordinary series-wound direct-current railway motors.

With the three-phase motor no special arrangements of any kind are necessary for regeneration. If a train, after running at a steady speed on the level or up-hill, comes to a descending gradient, the speed will rise slightly and the motors will regenerate without any change whatever in the electrical circuits.

As an example of the value of regeneration or recuperation, the case of a train weighing 300 tons and travelling on a 2 per cent. gradient may be cited. When running up the grade at $38\frac{1}{2}$ miles an hour, the input was 1,490 kilowatts, and when descending at a slightly higher speed, the train regenerated 660 kilowatts.

12. Motor and Generator Characteristics.—The application of the regenerative principle is illustrated by the curves in Fig. 2, which are plotted from the results of a test on a Ganz three-phase railway motor. The half of the diagram to the right of the ordinate *0 0* gives the curves for the machine as a motor, and the left half shows its performance as a generator. The curve *a* shows the speed, in miles per hour, of the locomotive and train driven by the motor, plotted against the pull on the drawbar, in pounds. Curve *a'*, shows the speed of the train when running down a gradient and giving a retarding thrust or negative pull on the drawbar, as shown by the horizontal scale.

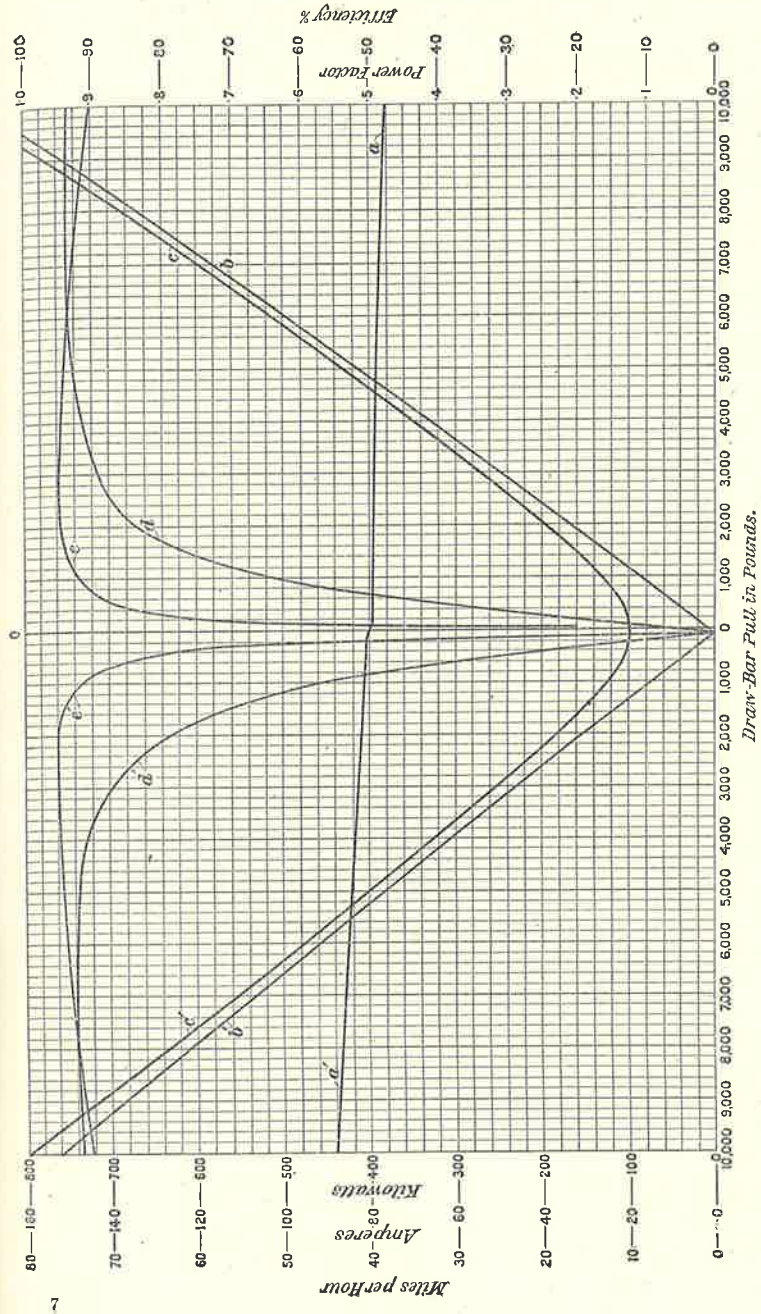

FIG. 2

The curves a, a' show that when the machine works as a motor the speed is always below 40 miles per hour and the slip is positive; when it works as a generator the speed is above synchronism and the slip is negative, the input also being negative. The negative value of the input signifies that energy is being returned by the machine to the line.

13. The curves b, b' in Fig. 2 show the number of kilowatts absorbed or returned by the machine, the part of the curve to the right of the ordinate $0\ 0$ representing power used, and that to the left the power regenerated. The current input and output are given by the curves c and c', respectively, and the power factor and efficiency when motoring and regenerating are given by the curves d, d' and e, e', respectively. The curves show that when the locomotive and train are running down-hill at 42 miles per hour, a total current of 71 amperes is being returned to the line, this corresponding to a regeneration of 355 kilowatts and a thrust or negative pull on the drawbar of 4,400 pounds. Although the kilowatt curves b, b' fall to zero, the current curves c, c' do not do so; this is because an exciting current of nearly 20 amperes is required to maintain the magnetism of the motor. If the pressure across the terminals of an induction motor fails when it is running as an asynchronous generator the generating action ceases, no matter how fast it may be driven, because there is no current available to maintain the magnetic field. For this and other reasons the regenerative action must not be relied on too greatly for a braking effect, but mechanical brakes must be provided for emergencies.

TYPICAL SHORT RUN WITH SIMPLE THREE-PHASE MOTOR

14. Energy Consumed in Accelerating.—In the simple type of three-phase motor, the input to the motor corresponding with any given pull is the same, whatever the speed. Hence, if a train is fitted with ordinary three-phase motors having rheostatic control, and not having any of the arrangements for saving energy which are usually employed, the input to the motors during the acceleration period must be kept constant. Fig. 3 shows the speed, distance, and kilowatts-input curves for a train

in which each motor has to deal with a total weight of 40 tons and the rate of acceleration is assumed at 1 foot per second per second. During the whole time that the train is accelerating, the input per motor is kept constant at 305 kilowatts until the train has reached a speed of $38\frac{1}{2}$ miles per hour. At this moment

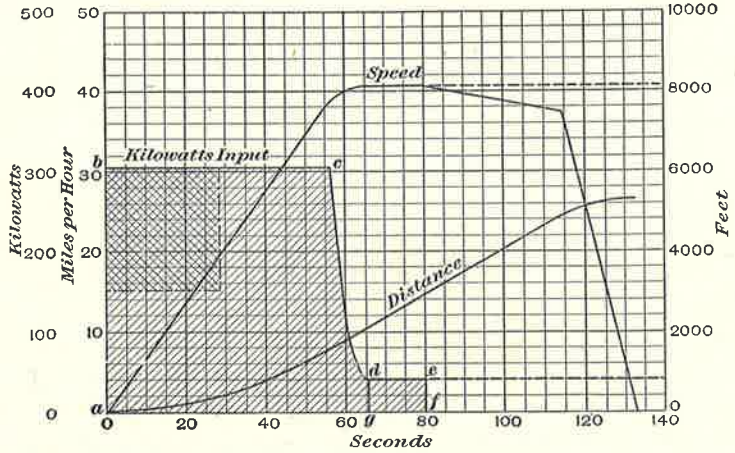

FIG. 3

the external rotor resistances have been reduced to zero, that is, the rotor windings have been short-circuited. As the rate of acceleration decreases, the pull of the motor falls off, until a balance is reached between pull and tractive resistance, at a speed of $40\frac{1}{2}$ miles an hour, when the input to the motor has fallen to 40 kilowatts.

15. Assuming a constant voltage of supply and a level track with no curves, the input remains at 40 kilowatts, as shown by d, e, Fig. 3, until coasting commences after a period of 80 seconds from the start. The brakes are applied after coasting for 34 seconds, and the train comes to rest after running for a total time of 133 seconds. The area $a\ b\ c\ d\ e\ f$ represents the energy input, and it will be noticed that the bulk of it is used up in accelerating. If the run had been 5 miles instead of 5,300 feet, as given by the distance curve, then the area $d\ e\ f\ g$ would have extended forwards, as shown by the dotted lines, for nearly

the whole run, and the area *a b c d g* would have become a much smaller proportion of the whole. This shows that for long runs the energy used in accelerating is not such an important matter as in short runs, and the waste of energy in resistances is not excessive. The connections may be arranged so that when two motors are used on a locomotive or motor coach the input during the period of acceleration may be reduced by the amount indicated by the cross-hatched portion of the area representing the energy input.

SPEED CONTROL OF INDUCTION MOTORS

RHEOSTATIC SYSTEM

16. Effect of Resistance in Rotor Circuit. — If resistance is inserted in the rotor circuit of an induction motor, the slip of the rotor will be increased, as it will require an increased E.M.F. to force the necessary current through the rotor conductors. The torque remains constant if the value of the rotor current and the magnetic flux do not change. The curves in Fig. 4 show the results of varying the resistance in the rotor circuit of a 67-horsepower three-phase induction motor. Curve *a* shows the variation in speed as the load or torque is varied, and the total resistance R in the secondary winding is equal to the resistance R_o of the winding alone. The no-load speed is nearly 600 revolutions per minute, and this falls off gradually until, at full-load torque of 592 pound-feet, the speed is 567 revolutions per minute. If an external resistance equal to that of the rotor windings is inserted in the rotor circuit, that is, $R = 2R_o$, the speed at which any given torque is obtained is reduced. Full-load torque of 592 pound-feet is obtained in this case at a speed of 530 revolutions per minute, as shown by curve *b*. Curves *c*, *d*, *e*, and *f* respectively show the relations of speed and torque for conditions where $R = 4R_o$, $R = 6{\cdot}45R_o$, $R = 12R_o$, and $R = 25R_o$. The maximum torque obtainable from the motor is 800 pound-feet, this being indicated by all the curves turning over at this point.

17. The rheostatic method of control of the speed of induction motors is extremely wasteful of energy and can only be used for cases where changes of speed are very seldom necessary, and where extreme simplicity is of more importance than high efficiency. If, for example, it is desired to reduce the speed of

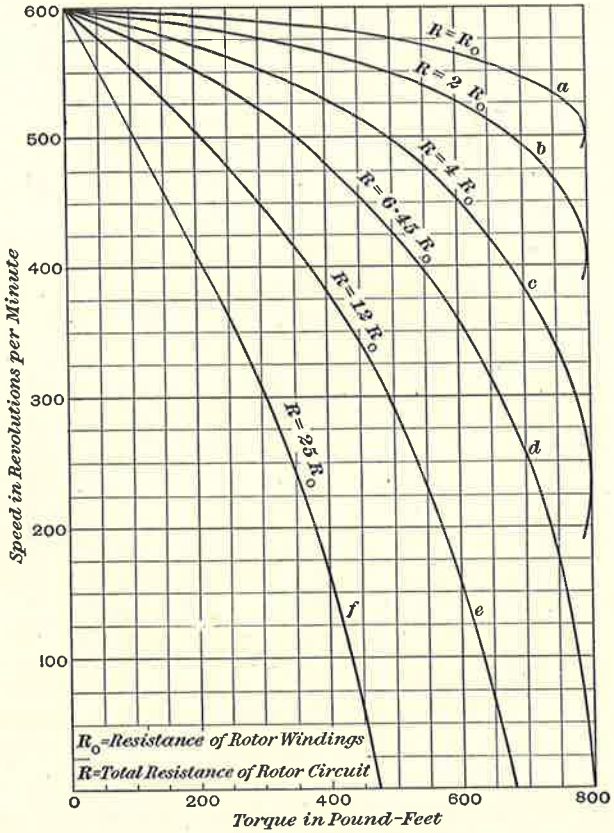

FIG. 4

a train to half its normal value by the use of resistances in the rotor circuit, then approximately half the energy supplied to the motor is wasted in the rotor circuit. In the majority of cases, the loss of energy that would be occasioned by this method of control is too serious to allow of its use, and one of the more modern methods which are about to be described is adopted.

CASCADE SYSTEM OF SPEED CONTROL

18. Characteristics of Cascade System.—The cascade system of controlling the speed of induction motors enables full advantage to be taken of the regenerative action of the machines. The motors retain their characteristic of constant speed, yet more than one constant speed is possible without rheostatic losses. Also, regeneration is possible, not only above the normal full speed, but over a fairly wide range of speeds below it. These improvements have brought the three-phase system into such a state of perfection that it can stand comparison, as far as energy consumption is concerned, with any other system.

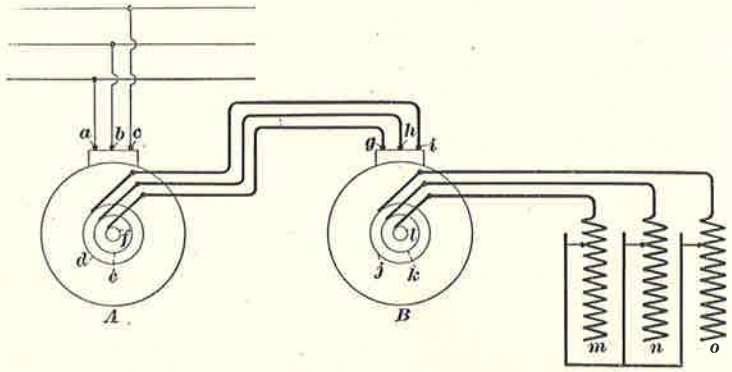

FIG. 5

19. Cascade Connections of Motors.—Three-phase motors may be connected in **cascade,** or **concatenation,** as it is sometimes called, as shown in Fig. 5. The three-phase supply is connected to the stator terminals *a, b, c* of the first, or *primary*, motor *A*, and the rotor windings of this motor are connected through the slip-rings *d, e, f* to the stator terminals *g, h, i* of the second, or *secondary*, motor *B*. The rotor windings of the second motor are connected through the slip-rings *j, k, l* to the resistances *m, n, o*.

If the two motors are mechanically coupled to car wheels of the same diameter, then the speeds of the two motors must be the same. The combination will run at such a speed that the frequency of the rotor currents in the first machine will be of

the proper value to supply the stator of the second machine. If the motors have the same number of poles, the combination will then run at half the synchronous speed of each motor separately. The synchronous speed of the pair of motors in cascade is called the **speed of cascade synchronism,** and at this speed the frequency in the rotor of the second motor is zero.

20. Compound Three-Phase Motors. — In Fig. 5, the rotor of the first motor is shown connected to the stator of the second. It makes no difference to the operation, however, if the connections are as shown in Fig. 6, in which the supply mains are connected to the stator terminals *a, b, c* of the first

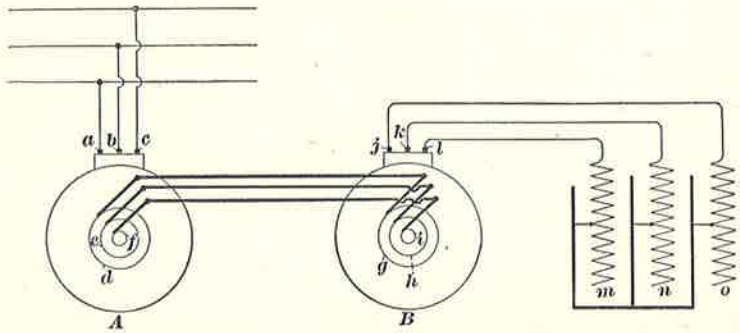

FIG. 6

motor *A*, and the rotors of the first and second motors are connected together through the two sets of slip-rings *d, e, f* and *g, h, i*. The stator terminals *j, k, l* of the second motor *B* are connected to the starting resistances *m, n, o*. The two motors can be connected together on the same shaft and the slip-rings *d, e, f* and *g, h, i* done away with, the connections being carried through from the rotor of motor *A* to that of motor *B*. The stators are then usually enclosed in the same housing. Motors constructed in this way are generally known as **compound three-phase motors.** They need not necessarily be arranged for cascade working.

21. Speed of Cascade Synchronism.—A formula for calculating the speed of cascade synchronism, when the frequency of

supply and the numbers of poles on the first and second motors are given, can be deduced as follows:

Let P = number of poles on first motor;
P' = number of poles on second motor;
$\sim$ = frequency of supply, cycles per second;
N = actual speed of combination, revolutions per minute.

Then, the normal synchronous speed of the first motor is $\frac{120 \sim}{P}$.

The speed with which the magnetic field of the first motor cuts the rotor is given by the difference between the speed of the field and the speed of the rotor, and is $\frac{120 \sim}{P} - N$. The frequency in the rotor of the first motor is therefore $\left(\frac{120 \sim}{P} - N\right)\frac{P}{120}$, and this is also the frequency in the stator of the second motor. The speed at which the field rotates in the second stator is therefore

$$\left(\frac{120 \sim}{P} - N\right)\frac{P}{120} \times \frac{120}{P'} = \frac{120 \sim - NP}{P'}$$

The difference between the speed of the field and the speed of the second rotor is $\frac{120 \sim - NP}{P'} - N$, and the frequency in the second rotor is $\left(\frac{120 \sim - NP}{P'} - N\right)\frac{P'}{120} = \sim - \frac{N(P+P')}{120}$.

At the speed of cascade synchronism, the frequency in the second rotor is zero. Thus, $\sim - \frac{N(P+P')}{120} = 0$, and the expression for the speed of the combination becomes

$$N = \frac{120 \sim}{P + P'}$$

22. Comparing this expression with the formula giving the synchronous speed of either motor alone, it is clear that the synchronous speed of the two motors connected in cascade is the same as the synchronous speed of a single motor wound for a number of poles equal to the sum of the poles in the first and in the second motors.

EXAMPLE 1.—Two similar motors are each wound with four poles, and the frequency of supply is 25 cycles per second. What is the speed of cascade synchronism?

SOLUTION.—In this case, $P = 4$, $P' = 4$, and $\sim = 25$. Substituting these values in the formula given in Art. **21**,

$$N = \frac{120 \times 25}{4 + 4} = 375 \text{ R.P.M. Ans.}$$

EXAMPLE 2.—Two three-phase motors are coupled in cascade, the first motor being wound with four poles and the second motor with six poles. The frequency of supply is 15 cycles per second. What will be the synchronous speed of each motor separately, and at what speed will the motors run when connected in cascade?

SOLUTION.—The synchronous speed of the first motor alone is $\frac{120 \times 15}{4} = 450$ R.P.M. Ans. The synchronous speed of the second motor alone is $\frac{120 \times 15}{6} = 300$ R.P.M. Ans. The cascade synchronous speed of the two motors is $\frac{120 \times 15}{4 + 6} = 180$ R.P.M. Ans.

23. Cascade Arrangements for Three Speeds.—If the primary and secondary motors are wound for different numbers of poles, three economical running speeds can be obtained without rheostatic losses. In the preceding example, if the primary motor is operated alone, a synchronous speed of 450 revolutions per minute is obtained. With the secondary motor running alone, the synchronous speed is 300 revolutions per minute, and with the primary and secondary motors in cascade, a speed of 180 revolutions per minute is obtained.

24. Regeneration With Two-Speed Equipment.—A pair of motors connected in cascade behave in precisely the same way as a single motor whose synchronous speed is the same as the cascade synchronous speed of the pair. A pair of motors in cascade will act as a motor at all speeds below cascade synchronism, and as a generator at speeds above cascade synchronism. If a train is hauled by a motor coach fitted with two pairs of three-phase motors, each wound for four poles, that is, two primary and two secondary motors, and the frequency of the supply is 25 cycles per second, there will be two economical

running speeds, namely, 750 revolutions per minute and 375 revolutions per minute, neglecting slip. When starting from rest and running up to full speed, the motors will be connected in cascade in pairs up to a speed of 375 revolutions.

25. Acceleration With Two-Speed Equipment.—When the motor coach is to be started from rest, the motors will be connected in cascade and resistance will be included in the rotor circuit of the secondary motor. As the speed increases, the resistance is reduced, and for the conditions outlined in the foregoing article a speed of nearly 375 revolutions per minute for the motors will be reached when the resistance is short-circuited. Further increase in speed is obtained by connecting the motors directly to the supply system having resistance in the secondary circuit of each, and gradually reducing this resistance until it is finally short-circuited and the speed is nearly 750 revolutions.

26. Retardation With Two-Speed Equipment.—In descending gradients the speed of the four-pole motors will rise slightly above 750 revolutions per minute, and will then hold the train in check by acting as generators. If it is desired to reduce the speed, resistance should be inserted in the rotor circuit of the secondary motor and the motors should be connected in cascade. As the speed is reduced owing to the regenerative action, the resistance should also be reduced. Below the speed of cascade synchronism the brakes on the train must be used to secure the desired retarding effect.

27. Acceleration With Three-Speed Equipment.—In order to illustrate the advantage of a three-speed equipment in accelerating a train, the action of a locomotive provided with two motors, one wound for eight poles and the other for twelve, will be considered. If the frequency is 15 cycles per second, the speed of the primary motor alone is $\frac{120 \times 15}{8} = 225$ revolutions per minute; the speed of the secondary motor is $\frac{120 \times 15}{12} = 150$ revolutions per minute; and the speed of the two when connected in cascade is $\frac{120 \times 15}{20} = 90$ revolutions per minute.

In starting from rest, the cascade connection is used and resistance is inserted in the rotor circuit of the secondary motor. After the speed has reached nearly 90 revolutions per minute, the resistance being cut out gradually, the secondary motor alone is connected to the supply mains and resistance is again inserted in the rotor circuit, this resistance being reduced as the speed increases. For speeds above 150 revolutions per minute, the primary motor is connected directly to the mains, resistance is included in the rotor circuit, and the secondary motor is disconnected. It may not be necessary to include resistance in the rotor circuit of the primary motor except when extra torque is required at a speed somewhat below the normal speed. The maximum speed of nearly 225 revolutions per minute is reached when the rotor of the primary motor is short-circuited.

28. Retardation With Three-Speed Equipment.—When it is necessary to reduce the speed of a train which is equipped with induction motors arranged for three speeds, the secondary motor is connected to the mains and the primary motor is cut out. Resistance is gradually cut out of the rotor circuit of the secondary motor until it is running at practically synchronous speed. The next step in the speed reduction is accomplished by connecting the two motors in cascade, with resistance in the circuit of the rotor of the secondary motor. This resistance is gradually reduced until the cascade synchronous speed is reached. Speeds below the cascade synchronous speed cannot be obtained by using the motors, as they cannot act as generators at low speeds.

29. Characteristic Curves of Motors in Cascade.—The characteristic curves previously given in Fig. 2 for a single motor relate to one of the earlier types of compound three-phase motor used on the Valtellina Railway in Northern Italy. The characteristic curves for the same machine when the primary and secondary motors are connected in cascade are shown in Fig. 7. Each compound motor consists of two distinct motors built on the same shaft and in the same outer case. The primary motor has eight poles and is wound for a pressure of 3,000 volts at a frequency of 15 cycles per second; the secondary motor also has eight poles, but is wound for a pressure of about 300 volts

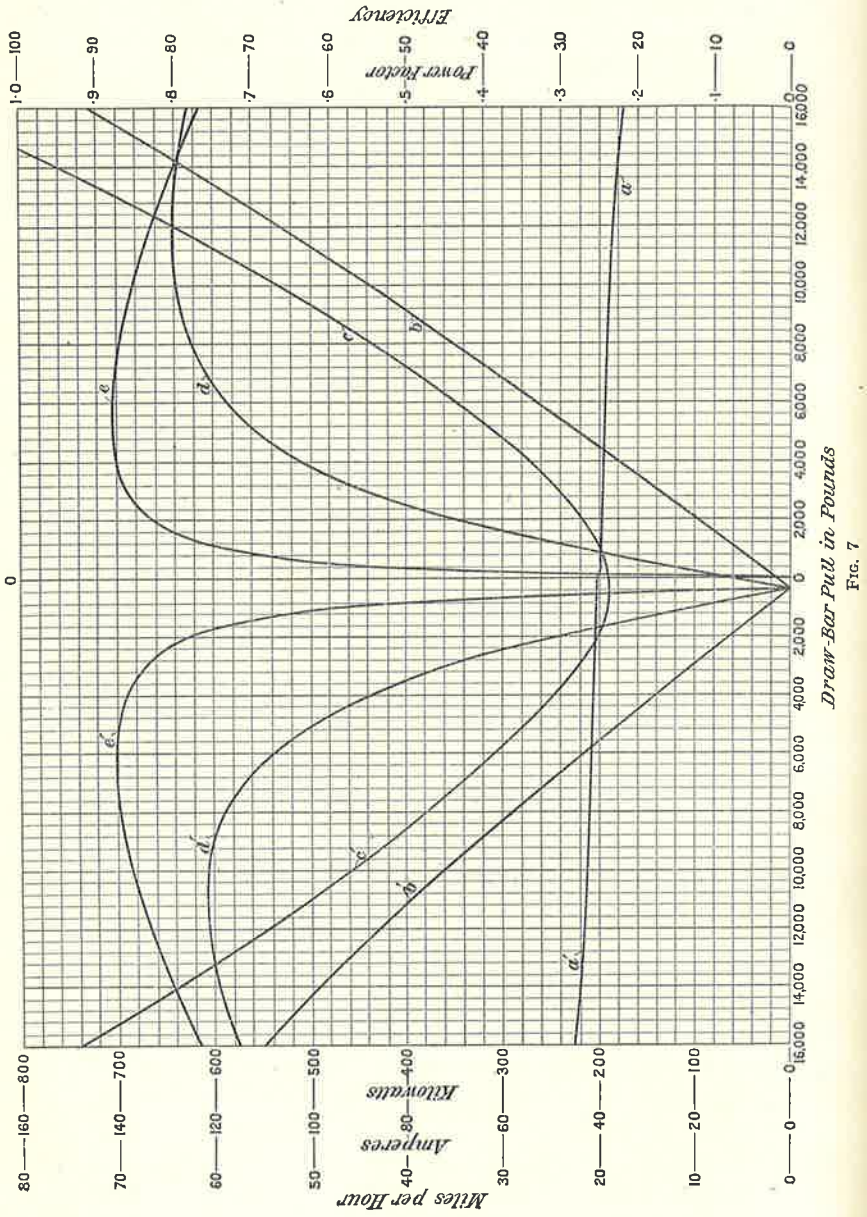

FIG. 7

The curves to the right of the ordinate *0 0* are those for the machine running cascade-connected as a motor, and those on the left of *0 0* show the performance of the machine when regenerating. The curves *a* and *a'* give the speed of the train, the motors in the first case driving it and in the second case being driven as generators by the train, the synchronous speed being 20 miles per hour. The curves *b* and *b'* show the input and output, in kilowatts, when motoring and regenerating, and the curves *c* and *c'*, *d* and *d'*, and *e* and *e'* show the current, power factor, and efficiency, respectively, under motoring and regenerating conditions.

30. Comparison of Curves.—The summary of a comparison of some of the points on the curves in Fig. 2 and in Fig. 7 is given in Table I. The maximum values of the power factor of

TABLE I

COMPARISON OF CHARACTERISTICS OF SINGLE MOTOR WITH CHARACTERISTICS OF CASCADE-CONNECTED MOTORS

Characteristic	Single Motor		Cascade Motors	
	Motoring	Regenerating	Motoring	Regenerating
Maximum power factor . . .	·934	·925	·80	·76
Maximum efficiency . . .	94·5	95·0	88·0	87·5
Speed, miles per hour . . .	38·5 to 40	40 to 42	17·4 to 20	20 to 22·7
Maximum kilowatts . . .	850	750	728	550

a single motor when motoring and regenerating are given in the table as ·934 and ·925, respectively, while, when the motors are in cascade, the maximum values are ·80 and ·76. The fall of power factor when in cascade is due to the fact that the lagging

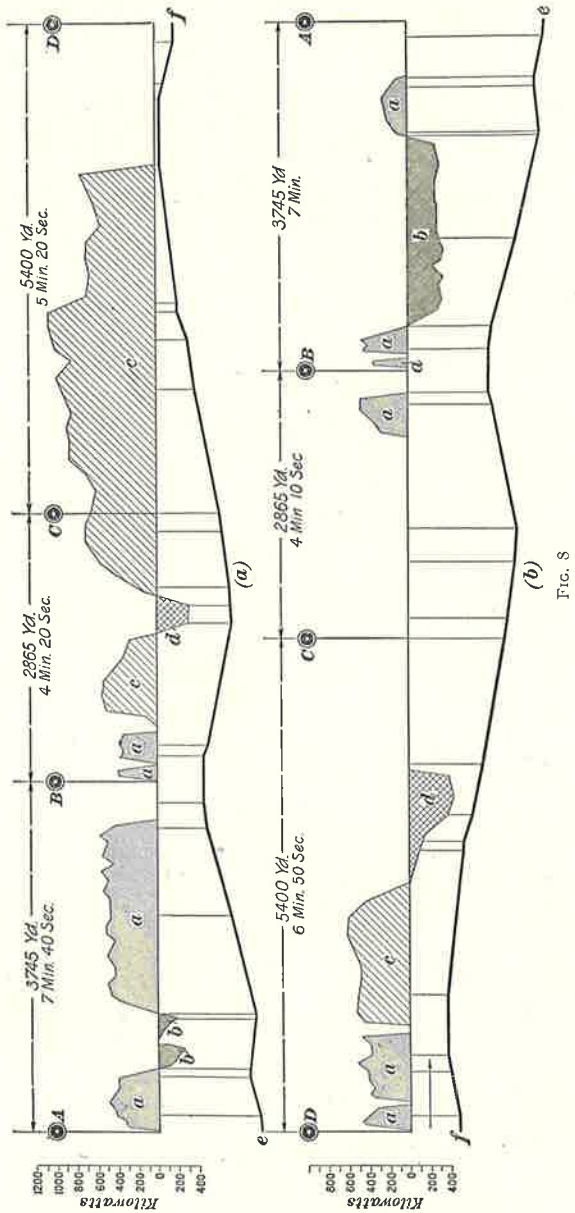

FIG. 8

current for magnetizing the secondary motor has to be supplied from the rotor of the primary motor. Thus, sufficient lagging current to magnetize both motors has to flow into the stator of the primary motor. It is necessary when motors are to be worked in cascade that each machine should have a high power factor when run separately, in order that the power factor when in cascade shall not be too low. The overload capacity of any induction motor depends on the maximum value of the power factor, so that the importance of making it as high as possible is at once evident.

31. Absorption and Regeneration of Energy.—The energy absorbed and regenerated by a train propelled by three-phase motors arranged for two-speed cascade control is represented graphically in Fig. 8. The train weighed 224 tons and was hauled by a locomotive weighing 62 tons, which was fitted with compound three-phase motors. Fig. 8 (*a*) gives the results when the train travelled from *A* to *D*, and Fig. 8 (*b*) when it travelled in the opposite direction. In the shaded areas, the horizontal line represents distance, the actual distances between stations and the time taken to traverse them being marked on the diagram. The vertical height of the curve above the base line represents kilowatts supplied to the locomotive, and the vertical distance below the line represents kilowatts regenerated. The areas *a*, closely shaded with thin lines, represent energy absorbed by the locomotive at half speed. The areas *b*, closely cross-hatched with fine lines, show the energy regenerated at half speed. The open-shaded areas *c* represent the energy taken at full speed, and the open cross-hatched areas *d* show the energy regenerated at full speed. The gradients of the line are shown by curve *e f*. In the run from *A* to *D*, the train stopped at station *B*, but ran through station *C*. The maximum value of the power absorbed was about 1,000 kilowatts, and that of the power regenerated about 400 kilowatts. The actual amount of energy regenerated during this run was, however, very small, because the line is mostly up-hill, as shown by curve *e f*. In the run from *D* to *A*, the amount of energy regenerated was much larger in comparison with that absorbed. It will be noticed

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that the train coasted for quite a large part of the distance, the route being largely down-hill, as shown by curve *f e*, which is curve *e f* reversed.

POLE-CHANGING SYSTEM OF SPEED CONTROL

32. Principle of Action.—The speed at which any induction motor rotates when supplied with current at a given frequency depends primarily on the number of poles for which the motor is wound. Therefore, if the number of poles on the motor can be changed, there will be an economical running speed corresponding to each number of poles. For example, a motor wound for four poles, and provided with an arrangement for doubling this number, would, on a circuit having a frequency of 15 cycles per second, give two synchronous speeds, namely, $\frac{120 \times 15}{4}$ $= 450$ revolutions per minute and $\frac{120 \times 15}{8} = 225$ revolutions per minute.

By employing suitable windings, motors could be arranged to give more than two numbers of poles, but in practice, under the conditions that obtain in traction work, it has only been found necessary to provide means for changing the number of poles in the ratio of 1 to 2.

33. Method of Changing Connections and Poles.—The diagrams in Figs. 9 and 10 show the method of changing the connections to the stator windings of an induction motor in order to change the number of poles. Each of the phase windings of the three-phase stator is split up into two parts, a_1, a_2, b_1, b_2, c_1, c_2, which are connected up to form a closed winding, as shown in Figs. 9 (*a*) and 10 (*a*). Each half of each phase winding includes the coils per phase of alternate poles. The junctions *1*, *2*, *3*, *4*, *5*, and *6* of the windings are connected to the fingers of a barrel switch. The three-phase supply mains *x*, *y*, *z* are also connected to fingers on the barrel switch. The way in which the switch fingers are connected up by the contacts on the drum for the greatest number of poles, for example eight, is shown in Fig. 9 (*a*). At the instant when

current is flowing in along phases *x* and *y*, and out on phase *z*, the direction of current in the windings a_1, a_2, b_1, b_2, c_1, c_2 is as indicated by the arrows.

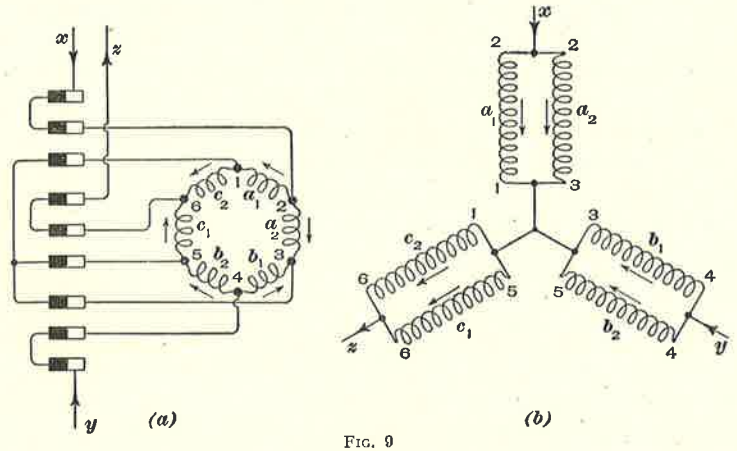


FIG. 9

34. The arrangement given by the connections outlined in the foregoing article can be found by tracing through the diagram in Fig. 9 (*a*), and is also shown in Fig. 9 (*b*). A star

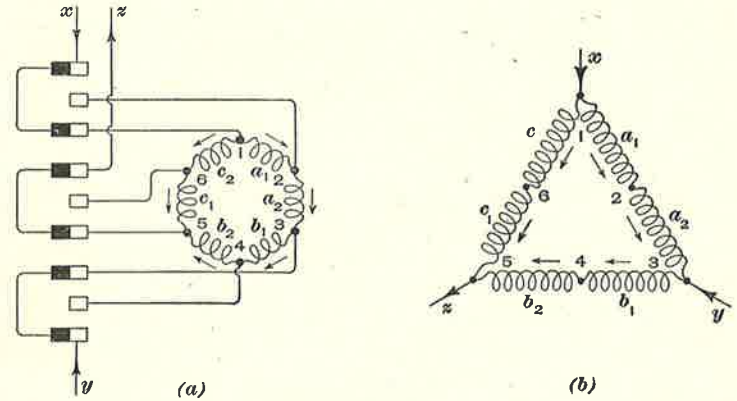


FIG. 10

connection is obtained, each arm of the star being composed of the two divisions of one phase, connected in parallel, the arrows showing the direction of current. In order to give the

connections for the minimum number of poles, for example four, the barrel of the switch is turned farther, and a second set of contacts connect up the switch fingers as shown in Fig. 10 (*a*), the equivalent winding obtained being given more simply in Fig. 10 (*b*), which is a delta connection, each arm of the delta consisting of the two divisions of one phase, in series. By comparing Figs. 9 and 10, it will be seen that the direction of current in the windings a_1, b_1, and c_1 is different in the two diagrams, while the current directions in windings a_2, b_2, and c_2 remain unaltered. The reversal of the direction of current through half the coils per phase in this case results in combining two poles into one and making the total number only half as great as before.

35. Winding Diagram. — A diagram of the windings of the stator of a three-phase induction motor arranged so that either eight or four poles may be obtained is shown in Fig. 11. The windings of each phase are shown in a distinctive colour, black, red, or blue, and the terminals are carried to the contact fingers of a barrel switch shown in the centre of the diagram. There are two slots per phase per pole for the eight-pole arrangement; the coils are indicated by a single line in order to simplify the diagram. The letters and numbers indicating the parts and terminals of the winding correspond to those used in Figs. 9 and 10.

36. The path of the current through the windings, assuming that contacts *d*, *e*, *f*, and *g*, Fig. 11, are in use and that current enters from the mains connected to fingers *x* and *y*, is as follows:

Finger *x*–contact *d*–finger *2–2–* | Finger *y*–contact *e*–finger *4–4–*

2–coil a_1–coil | *2*–coil a_2–coil | *4*–coil b_1–coil | *4*–coil b_2–coil

a_1–finger *1–* | a_2–*3*–finger *3–* | b_1–*3*–finger *3–* | b_2–*5*–finger *5–*

contact *f–*

finger *5–5–*coil c_1–coil c_1–*6–* | finger *1–1–1–*coil c_2–coil c_2–*6–*

finger *6*–contact *g*–main *z*.

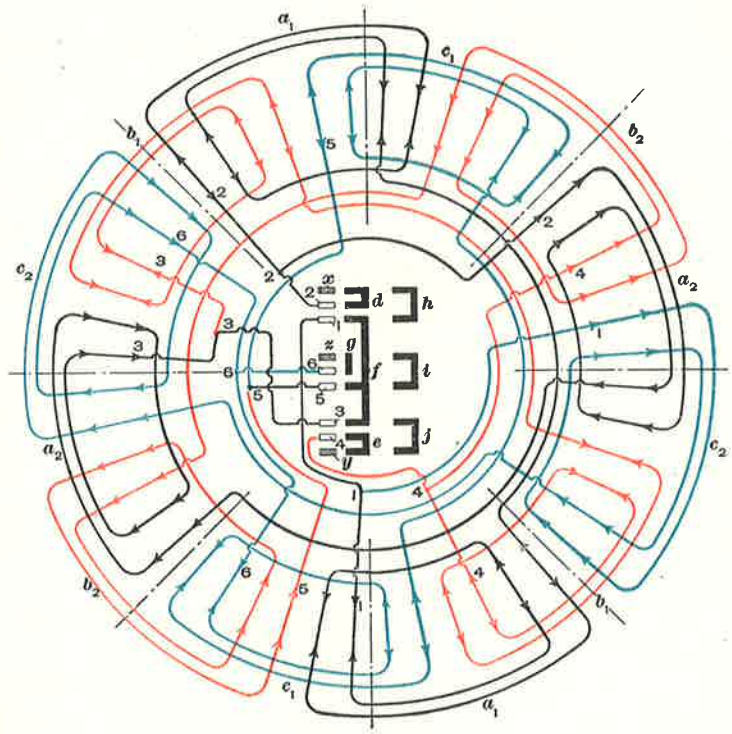


FIG. 11

The direction in which the current flows in the various conductors is indicated by the outer set of arrowheads.

37. In order to make connections to the windings, so that only four poles will be formed on the stator, the contacts *h*, *i*, *j*, Fig. 11, are brought into connection with the fingers of the switch. The direction of the current through the various conductors is indicated by the inner set of arrowheads. The windings are delta-connected, the current paths being as follows :

Finger *x*–contact *h*–finger *1–1*–

1–coil a_1–coil a_1–*2–2*–coil a_2–coil a_2–*3–3*–finger *3* – contact *j*–finger *y*.

1 – coil c_2 – coil c_2–*6–6*–coil c_1–coil c_1–*5*–

Finger *y*–contact *j*–finger *3–3–3*–coil b_1–coil b_1–*4–4*–coil b_2–coil b_2–*5*–

5–finger *5*–contact *i*–finger *z*.

38. In order to avoid confusion in showing how the poles are formed, the directions of current in the conductors, taken from Fig. 11, are shown again in Fig. 12. The outer set of conductors are marked with arrowheads showing the current directions for the eight-pole arrangement. As all the conductors in one pole region must have current flowing in the same direction, one pole region must end and another begin where the direction of current in the conductors changes. It will be seen that the conductors in the outer ring are divided into eight groups, the current flowing in opposite directions in alternate groups, and thus producing alternate north and south poles *N* and *S*.

39. The inner set of conductors and arrowheads in Fig. 12 show the current directions for the four-pole arrangement. Spaced between the four actual pole regions marked *N* and *S*, there are regions marked *A*. The currents flowing in the conductors in these regions to a large extent neutralize one another magnetically, and also set up small local magnetic fields, which slightly reduce the torque which the motor is capable of giving and lower the power factor. The four main polar regions are, however, obtained as shown. If the pressure between the supply terminals is *E* volts, each of the sections a_1, a_2, b_1, b_2, c_1, c_2,

Fig. 11, will receive a pressure of $\frac{E}{\sqrt{3}} = \cdot 577\ E$ volts when connected for eight poles. When connected for four poles, each section will receive $\frac{E}{2} = \cdot 5\ E$ volts. As the maximum torque which the motor is capable of giving depends on the square of

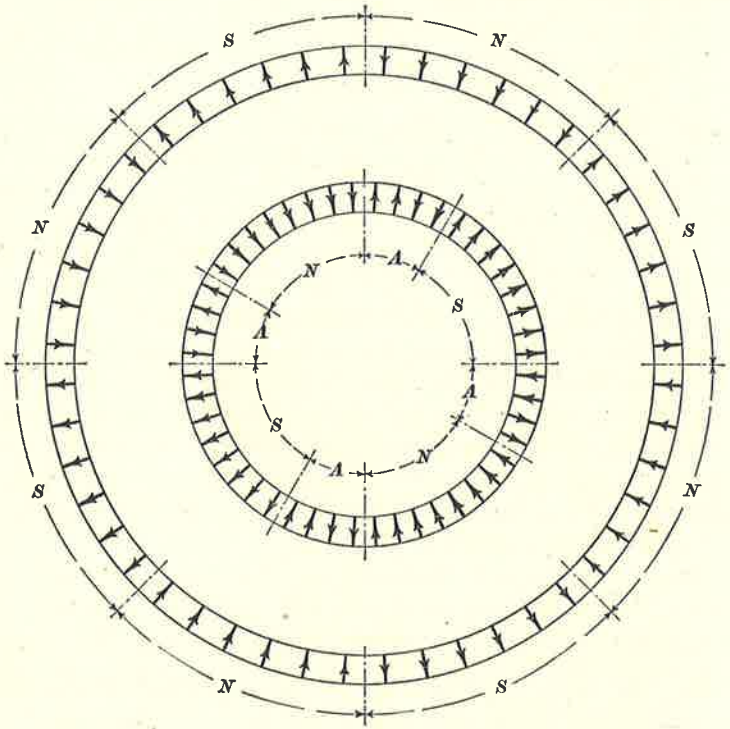


Fig. 12

the applied voltage, the maximum torque available is less than it would be with full voltage across the coils.

40. Rotor Connections.—At the same time that the number of poles on the stator is changed, the rotor windings must also be changed. This can be done by fitting the rotor slots with two separate three-phase windings, one for each number of poles,

and connecting each winding with a separate set of slip-rings. Then, when the barrel switch is moved over to alter the number of poles on the stator, the same movement raises the brushes from one set of slip-rings and lowers the other brushes on to the slip-rings of the second winding. If a squirrel-cage rotor is used, it will operate equally well with either number of poles on the stator, and the complication of slip-rings and brushes is avoided. For motors where three and four speeds are required, this is very important, as the number of slip-rings would be large. The use of squirrel-cage rotors for traction motors will be considered in detail later.

41. Compound Motors With Provision for Changing Number of Poles.—The pole-changing method of working has been developed beyond the stage already described by making use of compound three-phase motors. If one stator is wound for six and twelve poles, and the other for eight and sixteen poles, it is clear that there are four possible synchronous speeds. For example, with a frequency of 15 cycles per second, the speeds will be 300, 225, 150, and 112·5 revolutions per minute.

This development has been carried out by Brown, Boveri & Co. in their latest locomotives for the Simplon Tunnel Railway. The method of changing the poles on the stators is the same as that already described. A squirrel-cage rotor is used, the control of speed being effected by variation of the voltages applied to the stator windings and by using one or the other motor with the variation of the number of poles.

The elimination of external controlling resistances is a matter of considerable interest from the electrical as well as from the mechanical point of view. In railway work, the simplicity of construction and the avoidance of all rubbing contacts between brushes and slip-rings is often of greater importance than 1 or 2 per cent. difference in efficiency, and by careful design the desired simplicity can be obtained without excessive sacrifice of efficiency.

42. Determination of Resistance for a Squirrel-Cage Rotor. The disadvantage of using squirrel-cage rotors for traction motors is that, if they are designed as is usual for ordinary

induction motors, they give a very small starting torque and take a very large lagging current. This is because the resistance of a squirrel-cage rotor is small compared with its inductance, so that the rotor current, when the frequency is high, as at starting, lags very much behind the E.M.F. driving it. If the resistance of the rotor is increased, the rotor current is somewhat reduced, but it is brought more nearly into phase with the E.M.F., and the torque increases. On further increasing the rotor resistance, a point is reached when the reduction of starting torque produced by the reduction of rotor current is greater than the improvement in torque produced by the smaller angle of lag. It is clear, therefore, that there is a certain resistance for every squirrel-cage rotor which enables the motor to give its maximum starting torque.

43. There is, however, another point to be considered. Increasing the resistance of the rotor increases the copper loss in the rotor, and therefore reduces the efficiency of the motor. In an ordinary motor with a squirrel-cage rotor, the rotor copper loss is usually somewhat less than the stator copper loss. For a traction motor a large starting torque is essential, and a balance must be struck between the increased starting torque and the reduced efficiency, and the ratio of the rotor copper loss to the stator copper loss must be made considerably greater than unity. The curves in Fig. 13 show how the torque at starting varies for different ratios of rotor copper loss to stator copper loss. The lowest curve shows the specific current consumption, that is, the current required per 100 pound-feet of starting torque. The maximum torque is

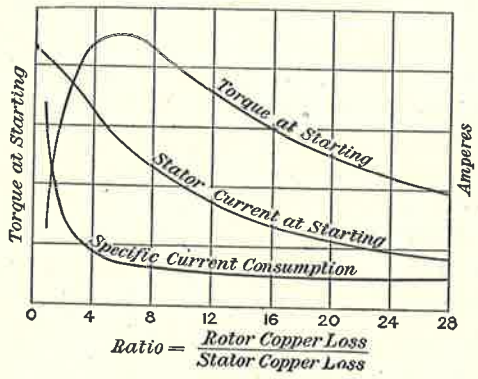


FIG. 13

obtained for the particular case taken, when the rotor copper loss is between 5 and 6 times the stator copper loss. This would, however, give too low an efficiency, and a sufficiently good starting torque is obtained when the ratio is reduced to a value of 3. The specific current consumption at this point is also fairly low.

44. Control of Motor With Squirrel-Cage Rotor. — As the resistance in a squirrel-cage rotor of an induction motor is invariable, the control of the torque and of the motor in general

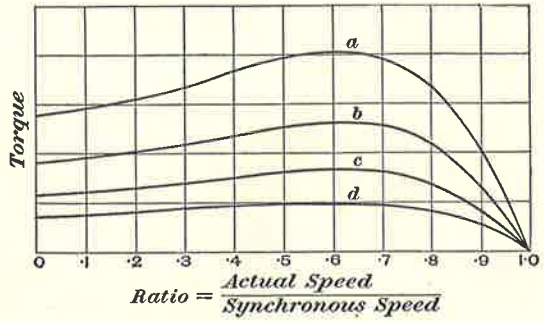


FIG. 14

must be effected by the only available means, namely, by varying the voltage applied to the stator windings. The windings

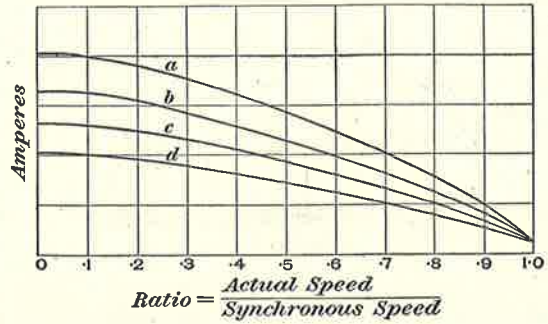


FIG. 15

receive current from suitably constructed transformers carried on the locomotive, arranged with a large number of tappings so that any desired voltage can be obtained. When starting up,

a low voltage is applied to the stator windings, and as the speed increases, the voltage is gradually raised to the full value. The variation of the torque corresponding to different voltages as the speed rises is shown in Fig. 14, curves *a*, *b*, *c*, *d* of torque against speed being given for the full voltage, and for values ·8,

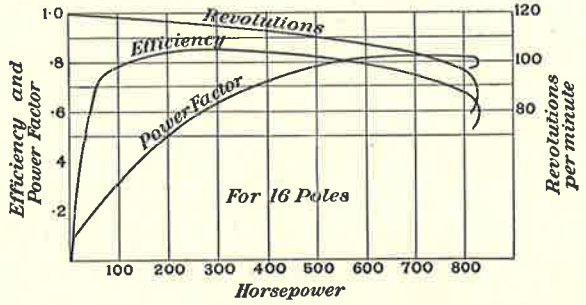


Fig. 16

·65, and ·5 of the full voltage, respectively. In Fig. 15 the corresponding variations of the stator current, with speed for the same values of the terminal voltage, are shown by the curves *a*, *b*, *c*, and *d*. The current in each case is greatest at starting, and gradually decreases as the speed approaches the synchronous speed.

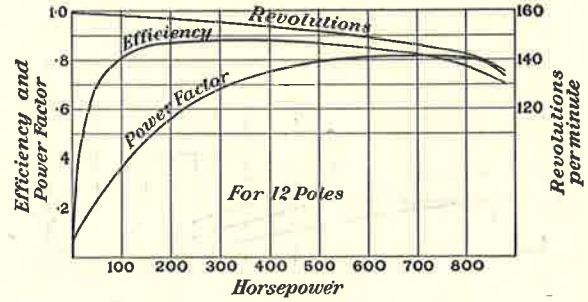


Fig. 17

45. Performance Curves for Compound Motor.—Curves showing the speed in revolutions per minute, efficiency, and power factor, of a compound three-phase induction motor when connected for sixteen, twelve, eight, and six poles, respectively, are given in Figs. 16, 17, 18, and 19. When the load is small, less

than 100 horsepower for the motor under consideration, the power factor is low, because the magnetizing current is a large proportion of the total current, especially for the arrangements of the winding giving large numbers of poles and low speeds. The shape of the efficiency curve is changed by changing the number of poles, but the effect is not the same in every case.

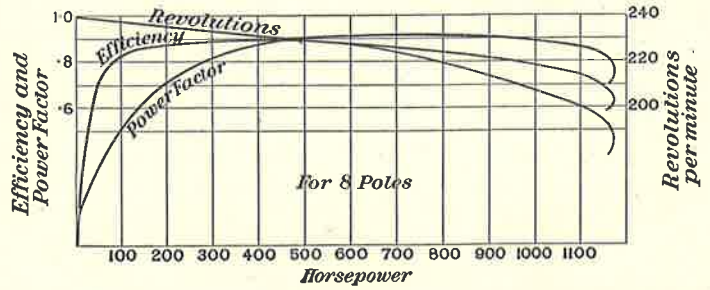


Fig. 18

It is possible to increase the power factor at small loads by reducing the pressure applied to the stator windings of the motor. The reduction in applied pressure causes a reduction in the overload capacity of the motor, but this is not serious under normal operating conditions. The performance curves

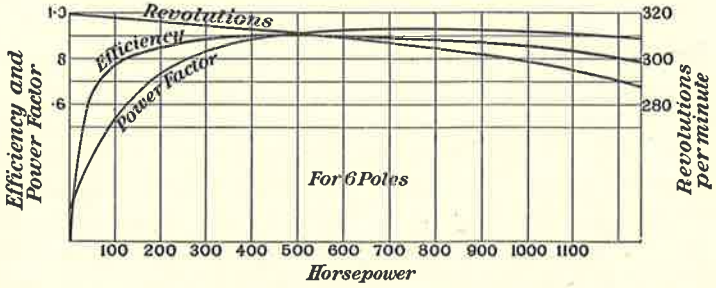


Fig. 19

in Figs. 20 and 21 show the influence of reducing the voltage on the efficiency and power factor at small loads. Fig. 20 refers to the motor working as a sixteen-pole machine, and Fig. 21 as a twelve-pole machine, the terminal voltage in both cases being reduced from 3,000 to 2,200 volts. As an example, compare

Figs. 17 and 21. In Fig. 17, the efficiency and power factor corresponding to 100 horsepower are ·81 and ·35, respectively, while, in Fig. 21, the corresponding values for the same output of 100 horsepower are ·87 and ·57. Thus, not only are the losses

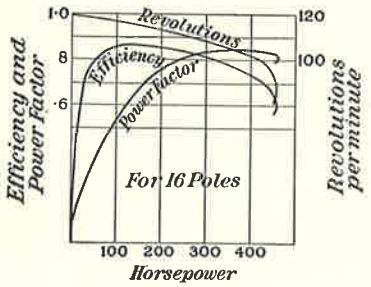


FIG. 20

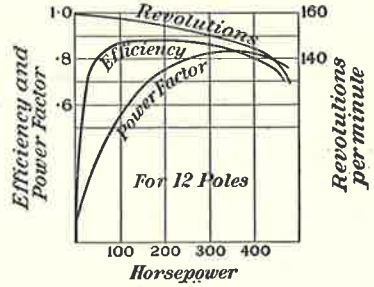


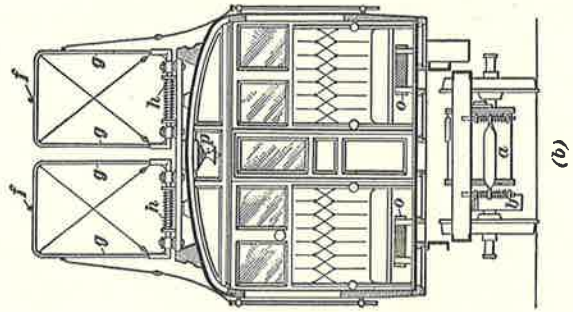
FIG. 21

in the motor reduced from 19 per cent. to 13 per cent., but the power factor is increased from ·35 to ·57, reducing the line current and therefore also the drop of voltage and the losses in the line.

EXAMPLES OF THREE-PHASE RAILWAYS

EQUIPMENT OF BURGDORF-THUN RAILWAY

46. The **Burgdorf-Thun three-phase railway** is a section of main line, 25 miles long, connecting the towns of Burgdorf and Thun, in Switzerland. It was equipped in 1899 by Brown, Boveri & Co., and is especially interesting as being the first main-line railway to be worked with three-phase alternating currents. The trolley-wire pressure is 750 volts, and the frequency 40 cycles per second. Current is supplied by the generators at a pressure of 4,000 volts, and the pressure is stepped up to 16,000 volts for the long-distance transmission system, and at various substations along the line is stepped down to 750 volts. There are two trolley wires, the rails forming the third conductor. The passenger trains consist of motor coaches and trailers, and run at a speed of $22\frac{1}{2}$ miles per hour. The luggage trains normally run at $11\frac{1}{4}$ miles per hour, and are



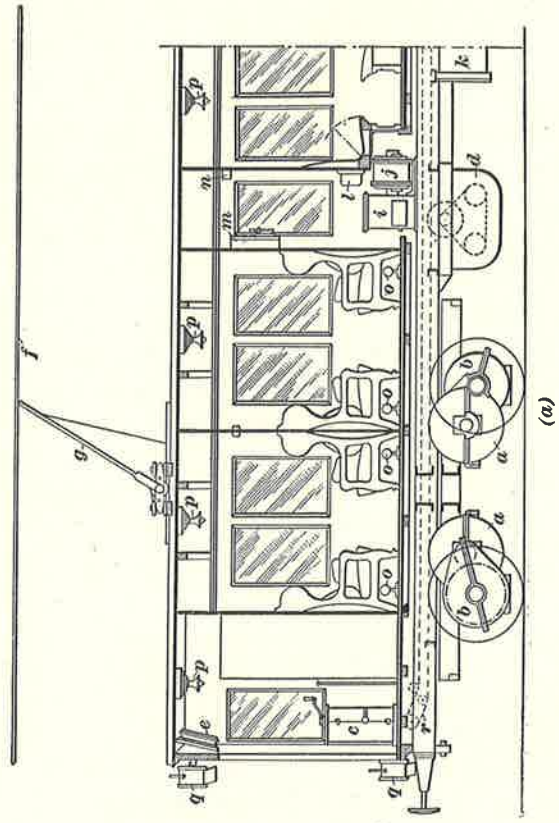


FIG. 22

hauled by locomotives. Two sets of gear-wheels on the locomotive enable the speed to be increased to $22\frac{1}{2}$ miles an hour when necessary.

47. Equipment of Motor Coaches.—Each motor coach on the Burgdorf-Thun Railway is fitted with four eight-pole 64-horse-power motors, each weighing 3,000 pounds, and having a synchronous speed of 600 revolutions per minute. Each motor is geared to one of the driving axles in the ordinary way through a forged-steel pinion and cast-steel wheel, the gear ratio being 3 to 1. The motors are suspended on springs, the suspension used being much the same as the nose suspension of a tramcar motor.

All four motors have their stator windings connected in parallel, and are started by means of rotor resistances. Fig. 22 shows the arrangement of the interior of a motor coach, view (*a*) being a longitudinal section through half a coach, and view (*b*) a transverse section. The details of the method of attaching the car body to the trucks are not given. The motors *a* are geared to the axle through a steel pinion and wheel enclosed in the casing *b*. The controller *c* is placed in a compartment at the end of the coach, and is mechanically coupled to the controller at the other end by means of gear-wheels and a chain *r*, so that the controller drums always occupy corresponding positions. The controlling resistance *d* is hung from the underframe of the coach. The current supplied is measured by the ammeter *e*, which is placed in such a position as to be easily read by the driver. Two trolley wires *f* are used, and the current collectors *g*, which are of the bow type, are pressed upwards against the wires by the springs *h*.

48. The air compressor *i*, Fig. 22, is used for operating the pneumatic brakes, and is driven by the motor *j*, which in turn is supplied with current at a pressure of 100 volts from the transformer *k*. The air pressure is kept at the desired value by means of the automatic switch *l*, which starts the compressor motor when the air pressure reaches a given minimum and stops it when the pressure rises to a given maximum. A small switchboard *m* is provided, on which the switches for the lighting and heating

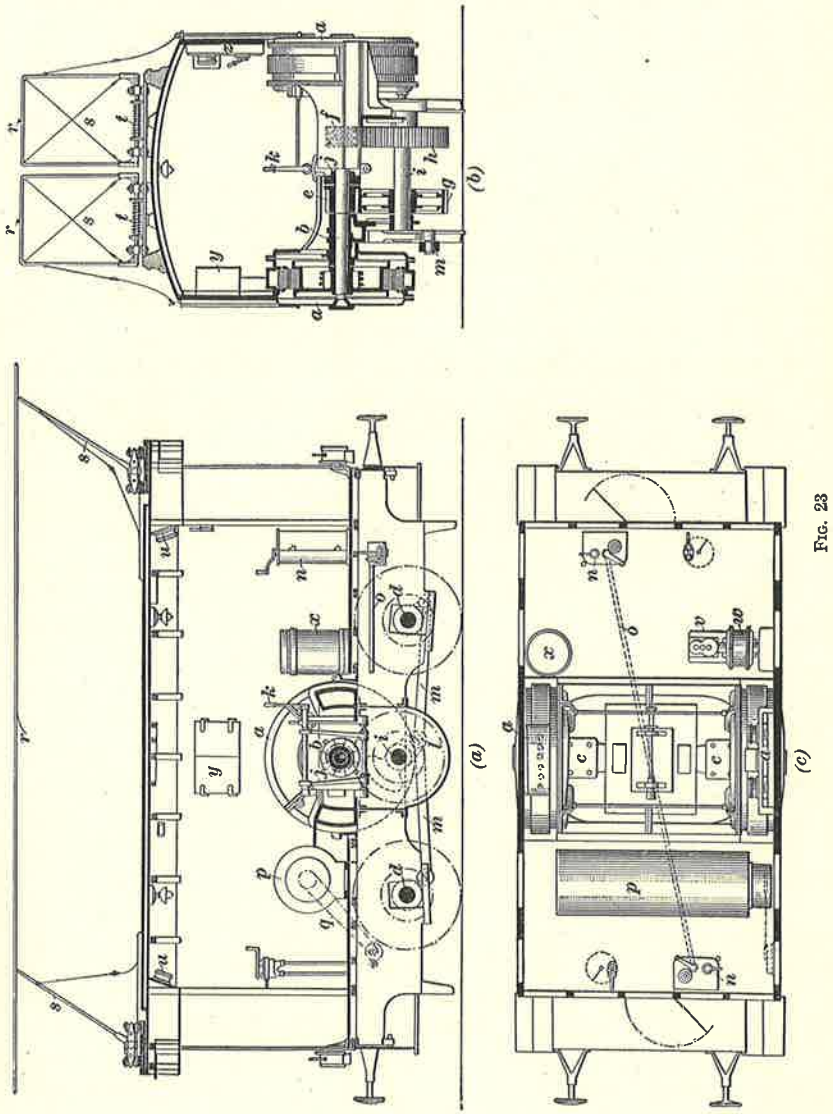


FIG. 23

circuits and the circuit-breakers for the compressor motor are placed. A lightning arrester is installed at *n*, in order that any static charges on the trolley wires may find an easy path to earth. The electric heaters *o* for warming the coach are situated beneath the seats, and the illumination is provided by lamps *p* fixed to the under side of the roof. Two head lights *q*, one at the top and one at the bottom of the coach body, are provided at each end. The coaches are fitted with pneumatic brakes of the Westinghouse type, and also with hand-brakes. Both these brakes are required only for stopping, as the speed of the train is controlled when descending inclines by the regenerative action of the motors.

49. Equipment of Locomotives.—The equipment of the locomotives in use on the Burgdorf-Thun Railway is illustrated in Fig. 23, view (*a*) being a longitudinal section, view (*b*) a transverse section, and view (*c*) a plan. Each locomotive is fitted with two sixteen-pole 150-horsepower motors *a*, having a synchronous speed of 300 revolutions per minute. They are mounted on the ends of a shaft *b*, which rotates in bearings *c* fastened on the truck frame midway between the two driving axles *d*. Two pinions *e* and *f* are mounted on the shaft *b*, and they gear with wheels *g* and *h* on an intermediate shaft *i*. These gear-wheels have two ratios, that of *e* and *g* being 1·88 to 1, and that of *f* and *h* being 3·72 to 1. Between the pinions *e* and *f* there is a clutch *j*, which can be moved along the shaft *b* by the handle *k* so as to engage with either of the pinions. In this way the speed of the locomotive may be 11 or 22 miles an hour while the motors run at constant speed. The connection between the shaft *i* and the driving wheels is made by means of crank *l* and coupling rods *m*.

50. The controllers *n*, Fig. 23, are coupled together by a shaft *o*, so that they cannot be in different positions. The rheostat for starting and controlling the motors is shown at *p*; it is operated by the chain *q* from either of the controllers. Current is collected from the two trolley wires *r* by the bow collectors *s*, which are pressed upwards by the springs *t*. When the driver is standing by either of the controllers, he has immediately in

front of him a 500-ampere ammeter *u*, from which he can tell the amount of current taken by the motors.

The air compressor *v* is driven by a small three-phase motor *w*, capable of giving 4 horsepower. A pressure of 100 volts, which is required by the compressor motor, is given by the step-down transformer *x*, this transformer also supplying current for light and heat. The fuses for the various circuits are contained in the sheet-steel box *y*, and on the opposite side of the driver's cab there is a switchboard *z*, on which are the instruments and switches for the lighting, heating, and compressor-motor circuits.

WIRING DIAGRAM FOR LOCOMOTIVE ON BURGDORF-THUN RAILWAY

51. Stator Circuit of Main Motors.—Fig. 24 shows the scheme of connections for the locomotive illustrated in Fig. 23. There are three separate circuits from the supply conductors to the various parts of the apparatus, one for each phase, but as they are all symmetrical, it will be sufficient to trace out one phase. Thus, in Fig. 24, the three supply conductors are the two trolley wires *a* and *a'* and the track rails *a''*, but the circuit from *a* only will be traced. Current is collected from *a* by the bow collectors *b*, and passes by way of bus-line *c* and the two ammeters *d*, *d'* to the controllers at *e*, *e'*. The two controllers are mechanically connected by a shaft and bevel gearing, so that when the driver actuates one of them the drum of the other moves in unison. When the proper movement has been made, the current of the phase under consideration leaves the controllers at *f*, *f'* and flows to the point *g*, part passing through fuse *h* to the terminal *i* of the stator of motor *j*, and part passing through fuse *h'* to the corresponding terminal *i'* of the stator of motor *j'*. The return circuit from the motor windings is to either conductor *a'* or *a''*.

52. Rotor Circuit.—The rotor circuit of the motors is entirely separate from the stator circuit. The slip-rings *k*, *k'*, Fig. 24, of the two motors *j* and *j'* are connected in parallel at *l* and to the resistances *m*, which can be gradually cut into or out of circuit by means of the movable contact-piece *n*. The movable

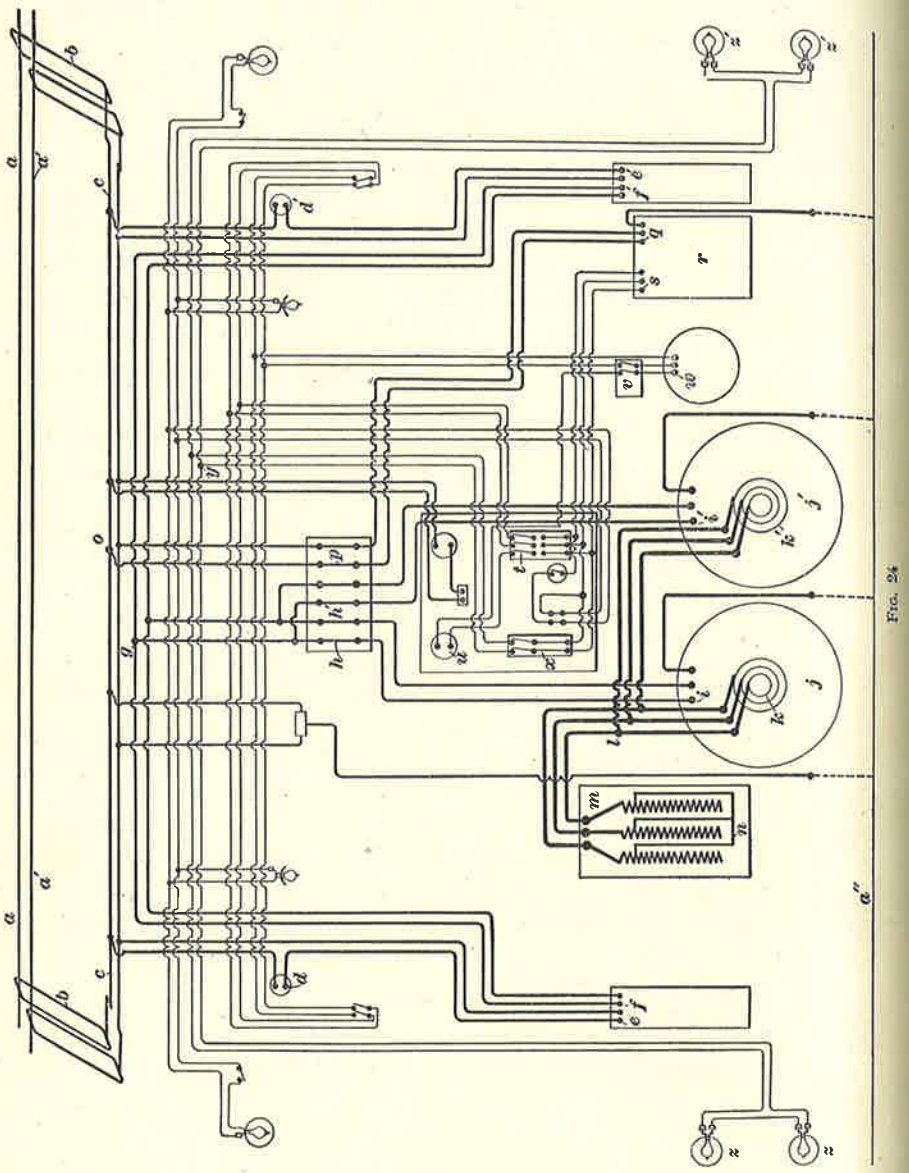


FIG. 24

part *n* of this rheostat is operated from the controller drum, so that when the driver rotates the drum he cuts resistance into or out of the rotor circuit.

53. Compressor-Motor Circuit.—The current for one phase of the compressor-motor circuit is taken from supply conductor *a*, through collector *b*, point *o* on the bus-line *c*, fuse *p* to primary terminal *q* of the step-down transformer *r*. From the secondary terminal *s* of the transformer the circuit is through one pole of the fuse and switch *t*, ammeter *u*, automatic switch *v* to terminal *w* of the compressor motor.

54. Head-Light Circuit.—The head lights are supplied from one phase of the step-down transformer *r*. Starting from the terminal *s*, the circuit is through one pole of the switch *x* and the low-tension bus-line *y* to the head lamps *z* or *z'*, the return path being similar to the one traced. The other lighting circuits of the locomotive are similarly connected to another phase on the low-tension side of the transformer *r*.

EQUIPMENT OF MOTOR COACHES FOR VALTELLINA RAILWAY

55. The **Valtellina Railway** is a section of main line about 67 miles long, situated near Lake Como, in North Italy. It was equipped on the three-phase system in 1900 by Ganz & Co., of Budapest. Power is generated at a hydro-electric station at 20,000 volts and is transmitted to substations along the line, where it is transformed down to 3,000 volts for supply to the conductors. There are two trolley wires, the track rails being used for the third conductor. Both motor coaches and locomotives are used on the system, the speed for passenger traffic being 42 miles per hour, and for freight service 21 miles per hour. This railway is interesting as being the first on which the principle of regeneration, or recuperation, was carried out fully, for it is not only made use of when the trains are descending grades, but is also used to return energy to the line when reducing the speed of the trains preparatory to stopping at stations.

56. General Arrangement of Motor Coaches.—Elevation and plan views, partly in section, are shown in Fig. 25 (*a*) and (*b*) of one of the motor coaches used on the Valtellina Railway. Current is taken from the trolley wires by one of the bow collectors *a*, and passes to a bus-line connected to the distribution boxes *b*. It then passes through the combined main and reversing switches *c*, which are operated by compressed air, and to the stators of the primary motors, one of which is shown at *d*. The motors are of the gearless type, the rotors being mounted on sleeves through which the wheel axles pass. Each pair of wheels is driven from its rotor through a link motion similar to that shown at *e*. This method of coupling enables the wheel axles to move relatively to the motors, and allows the motors to be spring-suspended. Every coach is furnished with four motors, two of which are wound for 3,000 volts and two for 300 volts. From starting, up to half speed, each high-tension motor is connected in cascade with a low-tension motor ; from half speed to full speed the high-tension motors only are in circuit.

57. A controller *f*, Fig. 25, is situated at each end of each motor coach, and the rheostats *g*, by means of which the resistance in the rotor circuit is diminished or increased according to whether the motors are being started or stopped, are placed under the floor. These rheostats are of the liquid type, and have fixed electrodes, round which the liquid is forced by compressed air. The air compressor is shown at *h*, and is driven by the small three-phase motor *i*, which is supplied with current at 100 volts by an 8-kilowatt step-down transformer. This transformer also supplies the lighting and heating circuits. The compressor *h* forces air into the reservoir *j*, from which is taken the supply of compressed air for operating the main switches, trolley-raising device, liquid resistances for the rotor circuits, and brakes. The pressure of the air in the reservoir is kept constant by means of the automatic device *k*, which disconnects or connects the motor *i* as the pressure exceeds or falls below certain limits. The cylinder of the Westinghouse brake is shown at *l*, and *m* is a hand-brake, which can be used when required. A small hand pump is provided at *n* by the use of which the

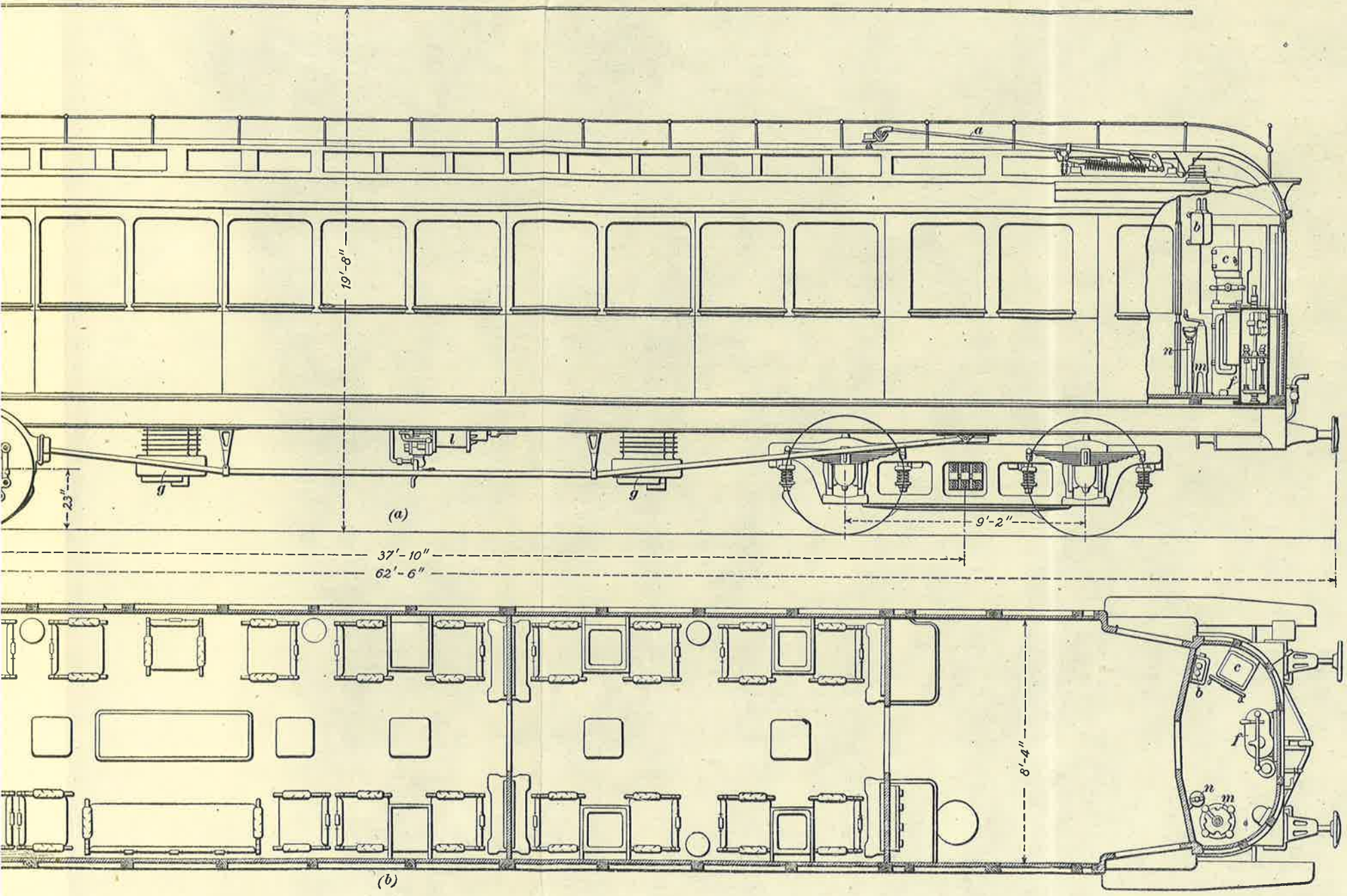


FIG. 25

otor Coaches.—Elevation and shown in Fig. 25 (*a*) and (*b*) l on the Valtellina Railway. wires by one of the bow col- connected to the distribution ne combined main and revers- d by compressed air, and to one of which is shown at *d*. , the rotors being mounted on les pass. Each pair of wheels link motion similar to that ing enables the wheel axles to nd allows the motors to be furnished with four motors, volts and two for 300 volts. each high-tension motor is nsion motor ; from half speed s only are in circuit.

situated at each end of each by means of which the resist- ned or increased according to rted or stopped, are placed are of the liquid type, and the liquid is forced by com- s shown at *h*, and is driven hich is supplied with current ep-down transformer. This ng and heating circuits. The ervoir *j*, from which is taken operating the main switches, ances for the rotor circuits, air in the reservoir is kept e device *k*, which disconnects essure exceeds or falls below Westinghouse brake is shown can be used when required. t *n* by the use of which the

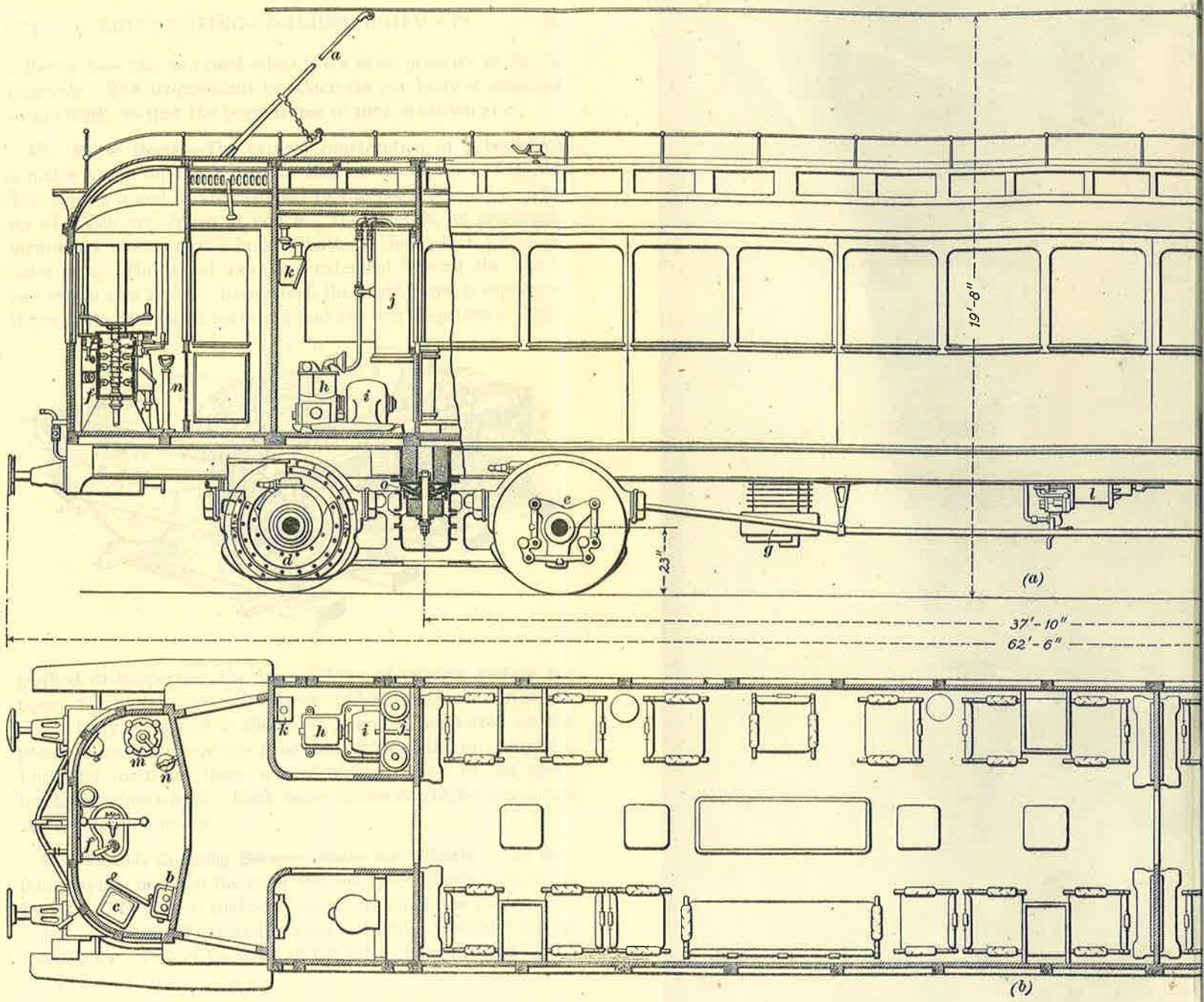


FIG. 25

collector bow can be raised when there is no pressure in the air reservoir. The arrangement by which the car body is attached to the bogie, so that the bogie is free to turn, is shown at *o*.

58. Motor Bogie.—The general construction of a bogie for a motor coach on the Valtellina Railway is shown in Fig. 26. The motors *a* and *a'* are fastened to the bogie frame by bolts, six of which are shown at end *b*. The rotor is, as previously mentioned, mounted on a hollow shaft, through which the wheel axles pass. The wheel axles are extended beyond the wheel, and run in axle boxes *c*, from which the bogie frame is supported through the laminated springs *d* and the spiral springs *e*. This

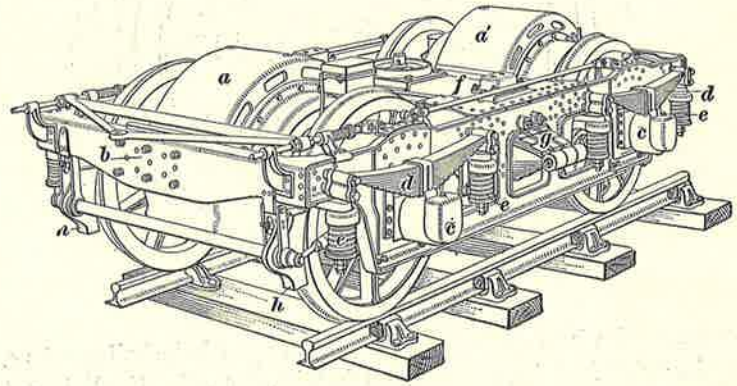


FIG. 26

method of supporting the bogie allows of relative motion between the motors and the wheels. The bolster on which the coach body is carried is shown at *f*, and is supported on the powerful laminated springs *g*, so that between the car body and the axles there are three sets of springs. Two of the brake blocks are shown at *h*. Each bogie carries one high-tension and one low-tension motor.

59. Flexible Coupling Between Rotor and Wheels.—The flexible coupling between the rotor and the track wheels is shown in Fig. 27. The hollow shaft, or sleeve, on which the rotor of the motor *a* is mounted is fitted at each end into a bracket *b* having three arms. Two of the arms of the bracket are pivoted to two

links *d*, *d*, the other ends of which are connected to two small bell-crank levers *e*. These bell-cranks are pivoted to two spokes *f* of the track wheel, and the free ends of the cranks are connected by the link *g*. When the rotor revolves it carries the three-armed bracket *b* with it, and this in turn transmits the rotative motion

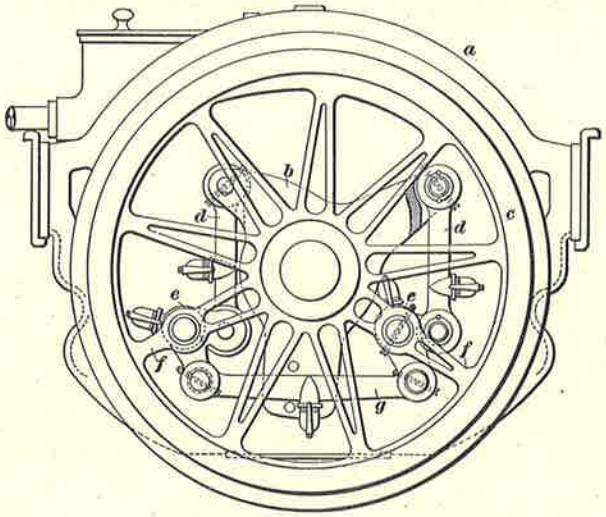


FIG. 27

to the track wheel through the links *d* and *g* and the bell-cranks *e*. If the rotor is not quite concentric with the axle, the links set themselves to suit, and the coupling allows the wheels to follow all the irregularities of the track, while the motors, as they are spring-borne, are carried smoothly.

60. Bow Collector.—Current is collected from the trolley wires by means of the bow collector shown in Fig. 28 (*a*), (*b*), and (*c*). View (*a*) is a side elevation, view (*b*) a front elevation, and view (*c*) a plan of the collector. Current is taken from the supply conductors by two copper cylinders, one of which is shown at *a*. The two cylinders are insulated from each other by a wooden roller *b*, and are supported in bearings at each end carried by a framework *c* of iron tubes. Carbon brushes are used to collect the current from the copper cylinders. The brushes are insulated from the frame *c*, and are connected

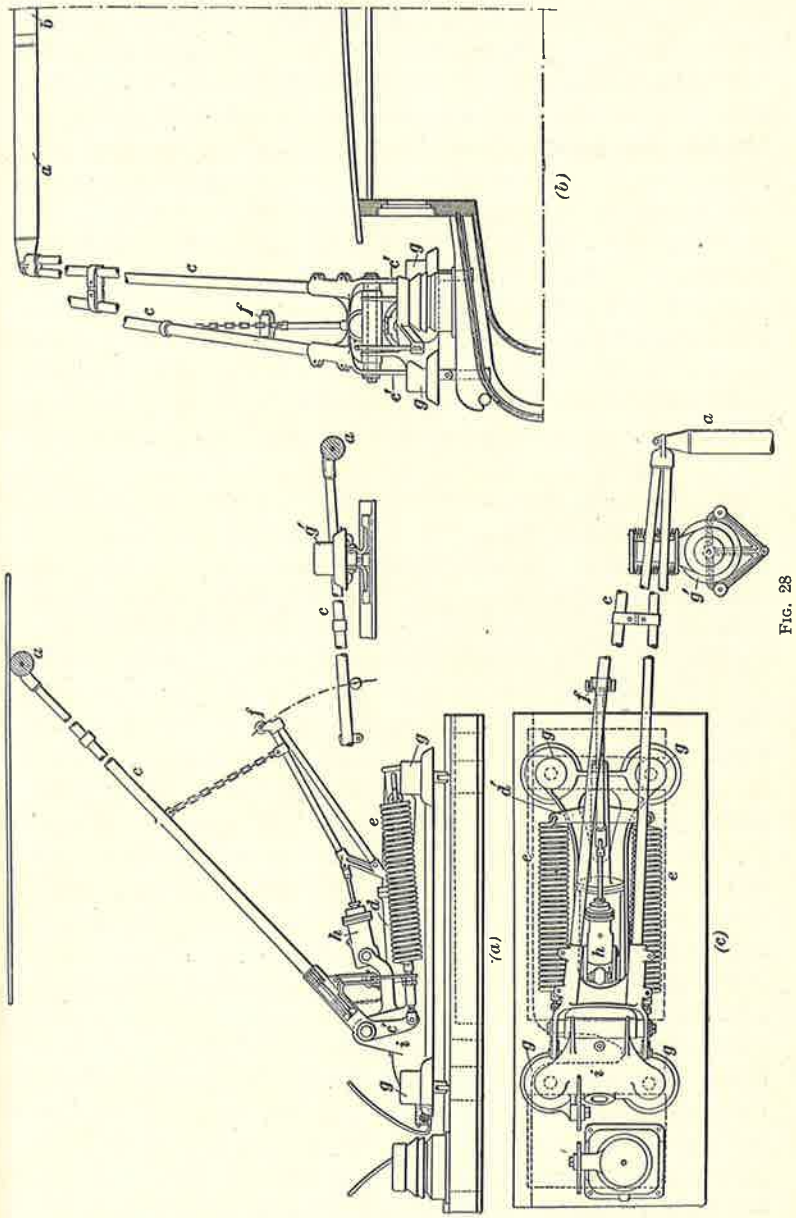


FIG. 28

to insulated cables supported on the frame. The air cylinder d is fitted with a piston and piston rod, the latter being connected to the crosshead d', which is fastened to the two tension springs e. The tension springs are also attached to the lever arm c' of the collector frame. When compressed air is admitted into the cylinder d, the piston is forced to the right, thus putting the springs e in tension and raising the collector frame. If the air in cylinder d is released, the weight of the frame will cause it to force the piston to the left and the collector will be lowered. It will drop quickly until the frame c strikes the buffer f, which will descend only gradually on account of the action of the dashpot h. The base i of the collector is mounted on insulators g carried on the roof of the coach. When the collector is down, it rests on a coil spring carried on special insulators g'.

61. Main and Reversing Switch, and Controller. — The combined **main and reversing switch** consists of a disc of insulating material, to the edge of which six copper pins are attached. When the switch is closed, these pins fit into sockets provided with metallic contact-pieces carried on a similar disc placed above the first. When the lower disc is raised, contact is made between the pins and the socket contacts, and when the disc is lowered, the circuit is broken, the rarefaction of air in the sockets extinguishing the arcs. This switch may be operated by means of a hand lever or by compressed air. As will be seen from the diagram of connections given in Fig. 30, the pins are joined in pairs, so that by rotating the disc through 60° the connections of two of the stator terminals to the overhead lines are interchanged, and therefore the direction of rotation of the motors is reversed.

The only places at which the high-tension wires are accessible are in the distribution box and the main switch. The cases of these parts of the apparatus are locked, and the key is placed in the trolley-raising apparatus. It can only be removed when the trolleys are lowered, that is, when the overhead wires are not connected, and the trolley cannot be raised until the key is in its place; the key, also, cannot be removed unless the cases are locked, so that there is little liability of danger due to the

cases being left open when the trolleys are making contact with the overhead wires.

The controllers present no very novel features; no circuits are broken at the controller contacts, and therefore no provision need be made for dealing with arcs. The controllers are provided with contacts for making connection to the resistances, and for connecting the high-tension motors singly, or in cascade, with the low-tension motors; in addition, each controller has a handle which controls the valve supplying compressed air for the purpose of operating the main switch. This switch cannot be operated until the controller handle is in one of the running positions, nor can the controller handle be turned to its off-position unless the handle operating the main switch has first been turned to the off-position, so that the main switch is open.

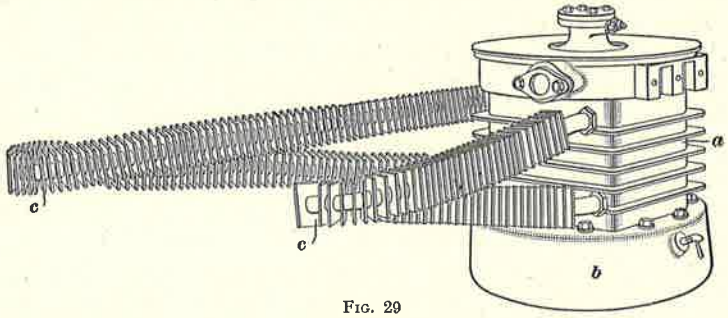


FIG. 29

62. Liquid Rheostat.—The resistance in the circuit of the rotor of each motor is varied by means of a liquid rheostat, a view of which is given in Fig. 29. The rheostat consists of a cast-iron receptacle a, in which three groups of plates of unequal length are contained, these three groups being joined to three terminals on the controller. An alkaline solution, which is contained in the base b of the rheostat, is forced into the upper part of the receptacle, and as soon as the liquid makes contact with the plates the rotor circuits of the motors are completed and the motors develop a turning effort. As the liquid rises the resistance decreases, and when it has reached its maximum height, the resistance is automatically short-circuited. In order to cool the liquid the case a is ribbed, and is furnished with heavily ribbed circulating pipes c offering a large radiating surface.

WIRING DIAGRAM FOR MOTOR COACH ON VALTELLINA RAILWAY

63. Main Motor Circuits.—A diagram of the connections of part of the electrical apparatus including one pair of motors only is given in Fig. 30, the connections for the second pair of motors and the remaining part of the apparatus being exactly similar. As the three phases of the three-phase circuit are symmetrical as far as the controller is concerned, it will be sufficient to trace through the connections for one phase, the return circuit in every case being through the other phases. Current is supplied by the two trolley wires a, a' and the rails a''. Starting from trolley wire a, current passes down the collector b, through the choking coil c, and into the bus-line d. It then passes through the main fuse e and, when the main switch A is closed, from contact f to contact g. From contact g, part of the current flows by way of wire h to one stator terminal i of the high-tension motor B, and part flows along the wire h' to the high-tension motor at the other end of the coach, which is not shown.

64. For cascade working, the rotor of motor B, Fig. 30, is connected to the stator of the low-tension motor C, the circuit for one phase being from terminal j on motor B, through contacts k and l on the controller D, and along wire m to stator terminal n of motor C. The rotor of motor C is connected to the liquid resistance E, the current in one phase starting from terminal o and passing by way of the contacts p and q on the controller to terminal r on the resistance E. When the liquid resistance is reduced to its lowest value, the rotor connections are short-circuited by a special switch s.

In order to run the coach at full speed, only the high-tension motors are used, and their rotors are connected directly to the liquid resistances. This is effected by turning the controller handle into the second position, so that the other pairs of contacts in the controller, such as k and k', Fig. 30, are connected together, thus putting terminal j of motor B in connection with one of the terminals of the resistance E.

65. Transformer and Lightning-Arrester Circuits.—The small step-down transformer for supplying the compressor motor,

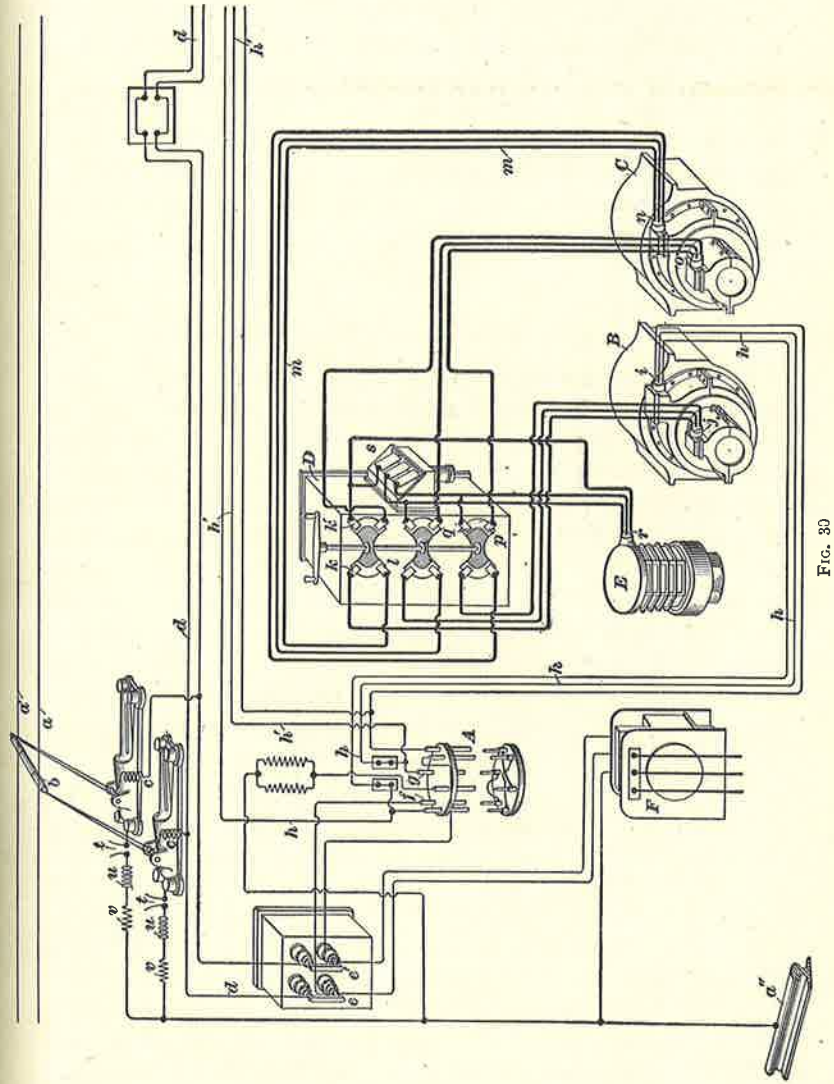


FIG. 30

heating, and lighting circuits is shown at F in Fig. 30. Two of its primary terminals are connected through the fuses e and e'

to the bus-lines, and thence to the trolley wires a and a', and the remaining primary terminal is connected to the rails a''.

There are two kinds of lightning arresters fitted to the car, namely, the horn type shown at t near the current collectors, and the Wurtz non-arcing metal type u in series with the horn type. Non-inductive resistances v are placed between the lightning arresters and earth to limit the rush of current which follows a lightning discharge. The choking coils c in the main circuit are for the purpose of preventing the static discharge from passing through the apparatus on the car.

TWO-SPEED LOCOMOTIVE FOR VALTELLINA RAILWAY

66. General Arrangement of Locomotive. — The two-speed locomotives for the Valtellina Railway are provided with two compound three-phase motors, which are coupled to the driving wheels by means of cranks and coupling rods. The general arrangement of the apparatus on the locomotive is shown in Fig. 31. The shafts of the rotors are fitted with cranks at each end, these cranks being placed at right angles to each other as on an ordinary steam locomotive. The cranks are provided with balance weights b, and are coupled together by the driving bar c. The driving bar transmits motion to the crankpin e of the central driving wheel a through a bearing having slides f, which permit vertical movement of the crankpin journal d. This vertical movement is necessary because the motors are mounted on the locomotive frame, which is supported on springs. The outer driving wheels, which are also marked a, are driven by means of coupling rods g jointed to the main driving bar c.

67. The outline of the motors is shown dotted at h, Fig. 31, and the controller is at i. The liquid rheostats j are placed at the front and back of the locomotive, and the small step-down transformer k at the extreme end. The compressor l supplies air to reservoirs m on the roof of the locomotive. The main high-tension switches are shown at n, and the low-tension switch at o, the electro-pneumatic relays being indicated at p. The pony wheels q of the locomotive are arranged so that they can

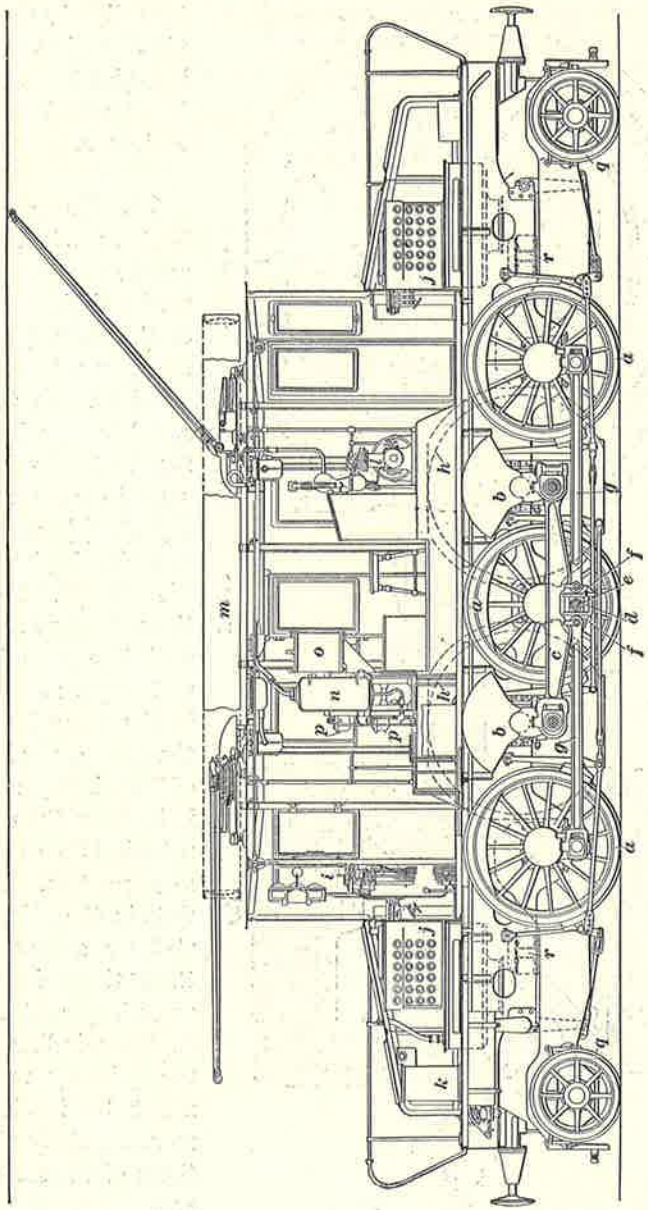


Fig. 31

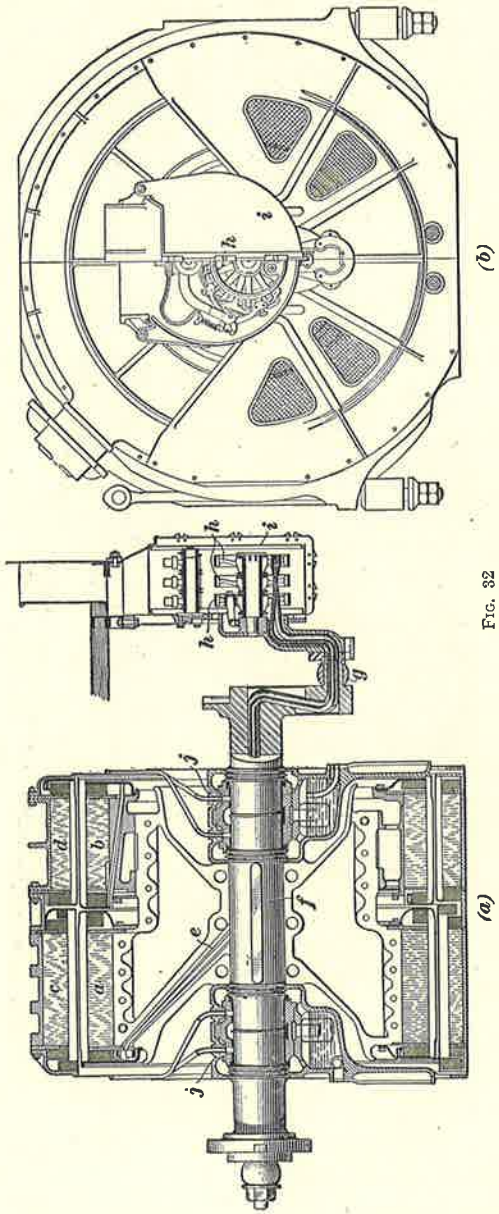


FIG. 32

turn slightly about a pivot *r*, thus allowing the locomotive to go round curves with ease.

68. Compound Motors of Locomotive.—A cross-sectional view of one of the three-phase compound motors used on the two-speed locomotive of the Valtellina Railway is shown in Fig. 32 (*a*), and an end view is given in Fig. 32 (*b*). Both the primary motor and the secondary motor are mounted in the same frame; the rotor *a*, view (*a*), of the primary motor is longer than the rotor *b* of the secondary motor. The slots in the primary stator *c* are deeper than those in the secondary stator *d*, as the windings of the primary motor must be insulated more carefully than those of the secondary.

69. The stator winding of the primary motor, Fig. 32, is connected to the 3,000-volt mains, and the windings on the two rotors are connected together, the junctions being connected by wires *e* which pass along the hollow shaft *f* and crank *g* to the slip-rings *h*. It will be noticed that the slip-rings are outside the case of the motor, and are enclosed in a sheet-iron case *i* made in two parts, which are bolted together. This arrangement of the brushes and slip-rings has two advantages: it ensures easy access to the brush gear for purposes of inspection, and it allows more space for the working parts of the motors. Each motor has eight poles and, the frequency being 15, the synchronous speed is 225 revolutions per minute, corresponding to a locomotive speed of 40 miles per hour. When the motors are connected in cascade the synchronous speed is 112·5 revolutions per minute.

The primary motor is made larger than the secondary motor because it is more often and longer in circuit, and so is liable to heat up more. In order to economize space, as well as give less chance of the shaft bending, the bearings *j*, *j* project inwards under the rotors of each motor.

WIRING DIAGRAM FOR TWO-SPEED LOCOMOTIVE ON VALTELLINA RAILWAY

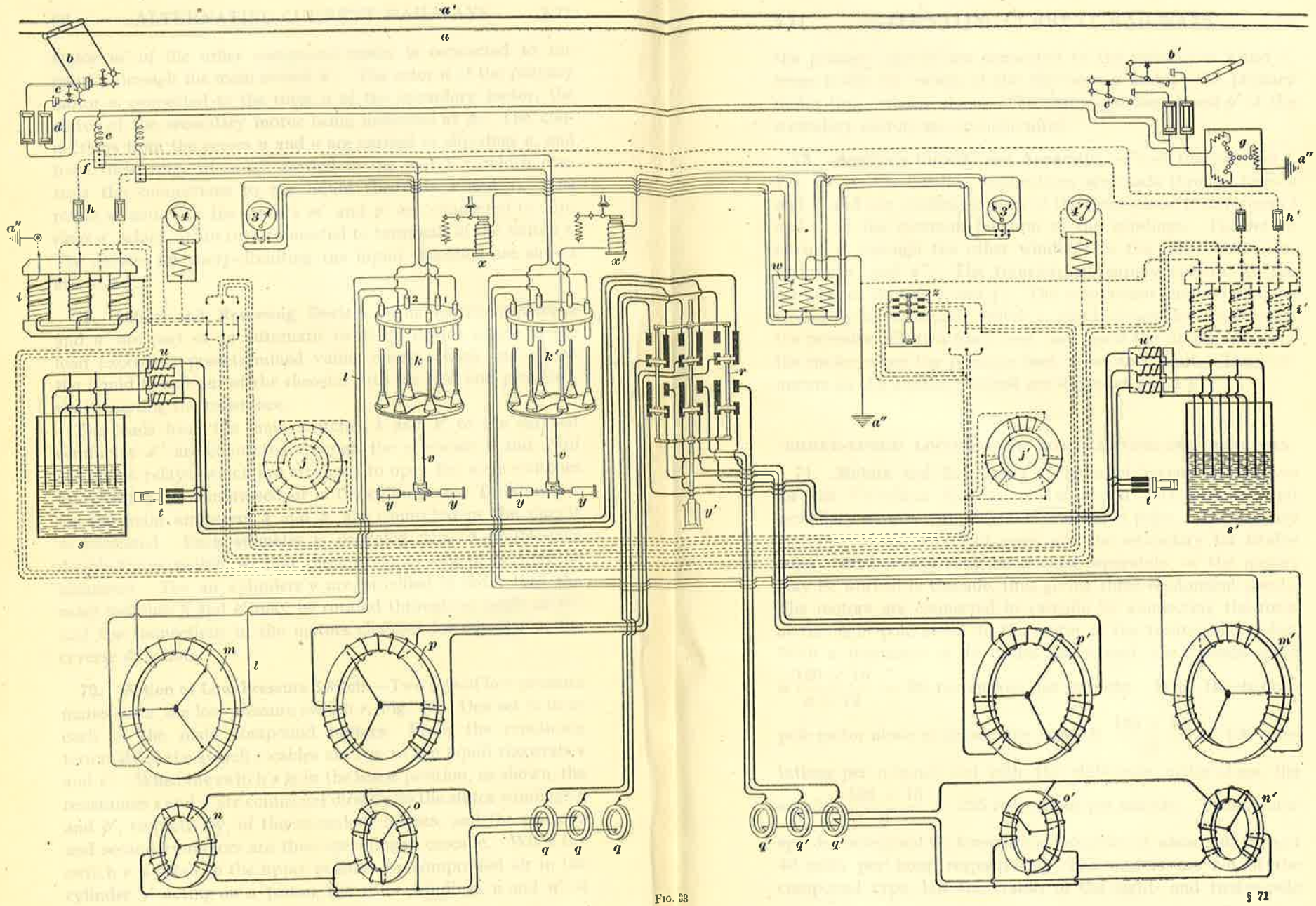
70. Main Motor Circuit.—A diagram of the connections of the electrical apparatus of a two-speed cascade locomotive is shown in Fig. 33. There are two supply conductors *a* and *a′*, and the track which is connected to earth is the third conductor, hence the earth connections are marked *a″* on the diagram. The path of the current in the main motor circuits is as follows for one phase: From conductor *a* through the collector *b*, switch *c*, which closes automatically when the collector *b* is raised to make contact with the supply conductors, fuse *d*, choking coil *e*, to terminal *f* on the bus-line. The automatic switch *c′* is shown in the open position as the collector *b′* is lowered. From *f*, current flows to contact *1* on the main switch *k*, and when this switch is closed the path is continued to contact *2*, wire *l*, and the winding of stator *m* of the primary motor. The primary

stator m' of the other compound motor is connected to the point f through the main switch k'. The rotor n of the primary motor is connected to the rotor o of the secondary motor, the stator of the secondary motor being indicated at p. The connections from the rotors n and o are carried to slip-rings q, and from these rings wires are carried to the switch r, which controls the connections to the liquid rheostats s and s'. The rotors n' and o' of the stators m' and p' are connected to slip-rings q', which are in turn connected to terminals of the switch r. The devices for short-circuiting the liquid rheostats are shown at t and t'.

71. Safety and Reversing Devices.—The electromagnets u and u' are part of an automatic overload device which, if the load exceeds a predetermined value, opens a cock and allows the liquid to run out of the rheostat into the reservoir provided, thus inserting the resistance.

The leads from the main switches k and k' to the earthed conductor a'' are connected through the solenoids x and x' of automatic relays, which are arranged to open the main switches by releasing the compressed air in the cylinders v. The shunts w for the main ammeters $\mathcal{A}$ and $\mathcal{A}'$ are connected in the circuit as indicated. Each ammeter is provided with a double-pole double-throw switch, so that the current in any phase may be measured. The air cylinders y are provided in order that the main switches k and k' may be rotated through an angle of 60° and the connections to the motors changed for running in the reverse direction.

72. Action of Low-Pressure Switch.—Two sets of low-pressure mains enter the low-pressure switch r, Fig. 33. One set is from each of the main compound motors. From the remaining terminals of the switch r cables are run to the liquid rheostats s and s'. When the switch r is in the lower position, as shown, the resistances s and s' are connected directly to the stator windings p and p', respectively, of the secondary motors, and the primary and secondary motors are thus operating in cascade. When the switch r is lifted to the upper position by compressed air in the cylinder y' acting on a piston, the rotor windings n and n' of


a'
a
b
c
d
e
f
h
a''
i
4
3
x
x'
2
1
k
k'
l
v
y
u
t
s
j
w
z
r
u'
v'
a''
3'
4'
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b'
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t'
s'
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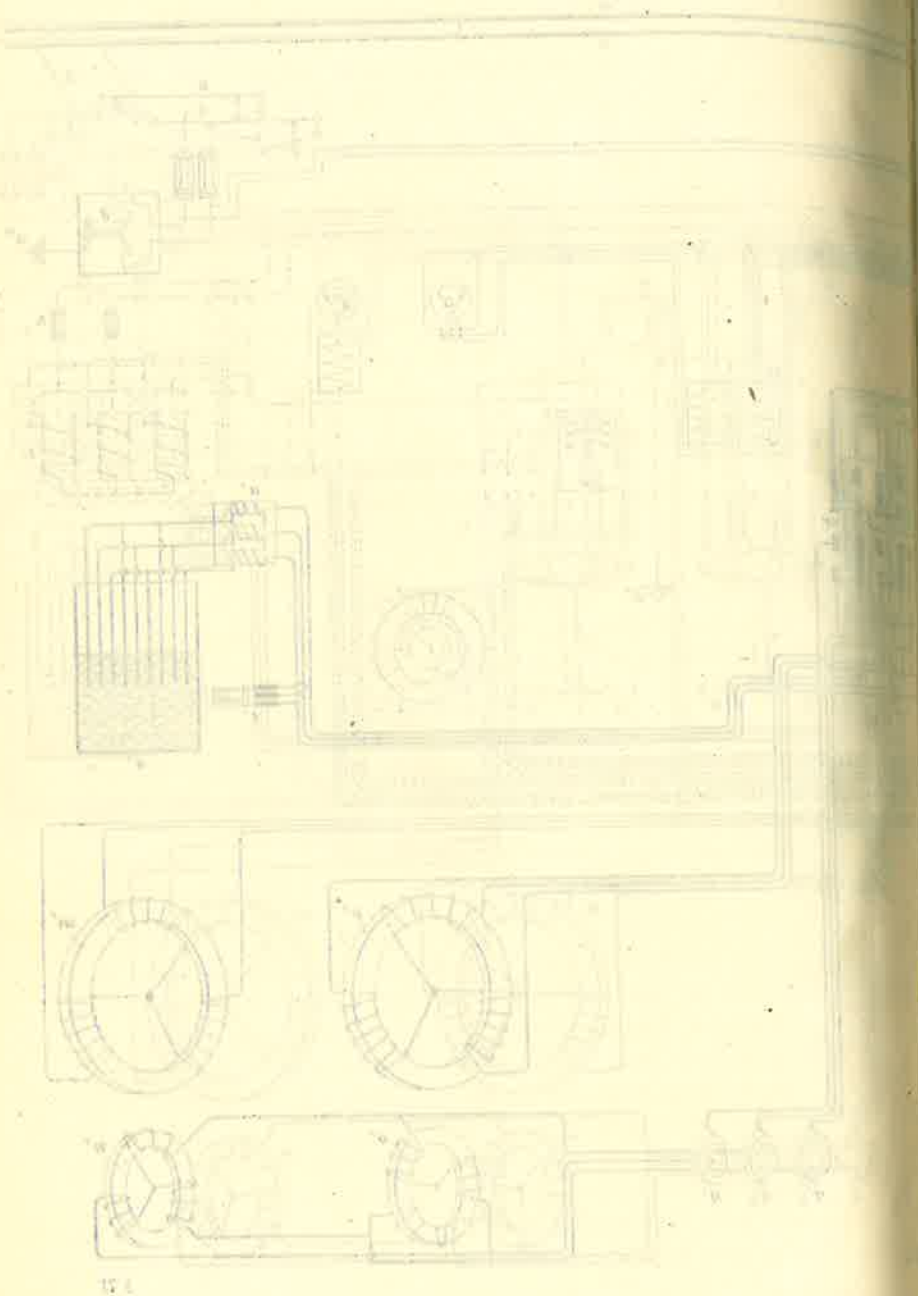
Fig. 33

§ 71



the primary motors are connected to the resistances s and s', respectively, by means of the slip-rings q and q', the primary motor thus running alone. The stator windings p and p' of the secondary motors are open-circuited.

73. Auxiliary Circuits and Apparatus.—From the junction f, Fig. 33, on the bus-line, connections are made through fuses h and h' and one winding of each of the three-phase transformers i and i' to the common junction of the windings. The return circuit is through the other windings to the other main conductors a' and a''. The transformers supply current for the compressor motors j and j'. The compressor motors are controlled by an automatic switch z, which closes the circuit when the pressure falls to a fixed limit, and opens the circuit and stops the motor when the pressure rises to another limit. The voltmeters on the auxiliary circuit are shown at 4 and $4'$.

THREE-SPEED LOCOMOTIVE FOR VALTELLINA RAILWAY

74. Motors and Equipment.—The most recent locomotives for the Valtellina Railway are equipped with primary and secondary motors with different numbers of poles. The primary motor is wound for eight poles and the secondary for twelve poles. Each motor may be worked separately, or the motors may be worked in cascade, thus giving three economical speeds. The motors are connected in cascade by connecting the rotor of the eight-pole motor to the stator of the twelve-pole motor. With a frequency of 15 cycles per second, the cascade speed is $\frac{120 \times 15}{8 + 12} = 90$ revolutions per minute. With the twelve-pole motor alone in circuit, the speed is $\frac{120 \times 15}{12} = 150$ revolutions per minute, and with the eight-pole motor alone, the speed is $\frac{120 \times 15}{8} = 225$ revolutions per minute. These motor speeds correspond to locomotive velocities of about 16, 26, and 40 miles per hour, respectively. The motors are not of the compound type, but the cranks of the eight- and twelve-pole

motors are connected together by a driving bar, and drive the wheels by means of cranks and coupling rods, as in the case of the two-speed locomotive. The arrangement of the various controlling appliances is much the same as for the two-speed locomotive, with the exception that additional pieces of apparatus are required.

75. Arrangement of Motor Windings.—When the motors are in cascade, the voltage applied to the stator of the twelve-pole motor is that generated in the rotor of the eight-pole motor. When the twelve-pole motor is operating by itself, its stator receives the full line pressure of 3,000 volts. It is necessary,

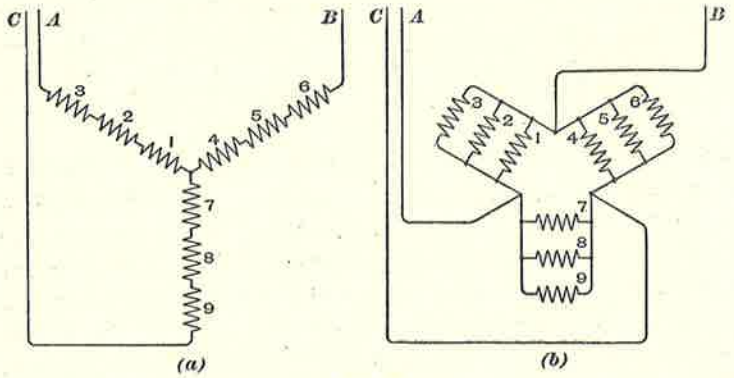


FIG. 34

therefore, either that the rotor of the eight-pole motor should be wound to give 3,000 volts when running in cascade, or that the stator of the twelve-pole motor should be reconnected for a lower voltage when used in cascade. The latter alternative has been adopted, and the connections used for the two voltages are shown in Fig. 34 (*a*) and (*b*). Each phase of the winding is divided up into three sections, as shown in view (*a*), phase *A* being divided into sections numbered *1*, *2*, and *3*, phase *B* into sections numbered *4*, *5*, and *6*, and phase *C* into sections numbered *7*, *8*, and *9*, the sections of each phase being connected in series, and the phases themselves being star- or **Y**-connected, for the full pressure of 3,000 volts. For cascade

working, the sections of each phase are connected in parallel and the phases themselves in delta, as shown in view (*b*).

76. Voltage Ratio.—If the correct voltage for each section of a phase of the motor winding is v volts, then, in the case shown in Fig. 34 (*a*), the voltage per phase is $3v$, and the voltage across the line is $3\sqrt{3}\,v$. In the case shown by Fig. 34 (*b*), the voltage across the line is equal to the voltage per phase, that is, to v. The ratio of the voltage for cascade connection to the voltage for direct connection is, therefore, $\frac{v}{3\sqrt{3}\,v} = \frac{1}{3\sqrt{3}} = \cdot 192$, approximately. The rotor of the eight-pole motor when running in cascade should therefore give $3{,}000 \times \cdot 192 = 576$ volts.

WIRING DIAGRAM FOR THREE-SPEED LOCOMOTIVE ON VALTELLINA RAILWAY

77. Cascade Connection of Motors.—The diagram of connections for the three-speed locomotive is given in Fig. 35. The compressor motor and auxiliary circuits are the same as for the two-speed locomotive, so that only the main circuits will be considered. The path through one phase winding when the motors are connected in cascade is as follows: From trolley wire *a*, through bow collector *b*, collector switch *c*, fuse *d*, choking coil *e*, terminal *f*, and, when main switch *g* is closed, to terminal *1* on the change-over switch *h*, which is placed on the contacts *4*, *5*, and *6*, thus connecting the stator windings of the eight-pole motor *o* directly to the mains *1*, *2*, and *3*. The slip-rings *28*, *29*, and *30* of the eight-pole motor *o* are connected to the fingers *28*, *29*, and *30* on the low-tension switch *m*, and these are joined by the contacts marked *cascade* to the fingers *A*, *B*, and *C*. These fingers are connected to similarly lettered fingers on the switch *i*. For example, finger *A* on switch *i* is connected by the contacts *k* to fingers *20*, *22*, and *24*, and also to fingers *7*, *9*, and *11*, the fingers being connected to similarly numbered terminals of the stator winding of the twelve-pole motor *l*. Similarly, finger *B* is joined to terminals *14*, *16*, *18*, *19*, *21*, and *23* of the stator winding, and finger *C* to terminals

8, *10*, *12*, *13*, *15*, and *17*. In this way, all the sections of one phase are connected in parallel, and the phases are connected in delta, as shown in Fig. 34 (*b*). The slip-rings *25*, *26*, and *27*, Fig. 35, of the twelve-pole motor *l* are connected by way of the similarly numbered fingers on switch *m* to the fingers *31*, *32*, and *33* which lead to the liquid resistance *n*.

78. Connection of Twelve-Pole Motor Alone.—For twelve-pole working of the motors the change-over switch *h*, Fig. 35, is in the position shown, and the current for one phase passes to contact finger *1* on the stator switch *i*. The set of contacts *j* are in contact with the fingers for twelve-pole connection, so that current passes from finger *1* to finger *7*, and so to terminal *7* on the stator winding of the twelve-pole motor *l*. The contacts on switch *i* connect terminals *8*, *9* and *10*, *11*, thus joining the various sections of the stator winding composing one phase in series. If the other phases are traced through, it will be seen that they are similarly connected to mains *2* and *3*. The three phases are connected in star, the points *12*, *18*, and *24* being joined together. This gives the stator connections shown diagrammatically in Fig. 34 (*a*). Returning to Fig. 35, from the slip-rings *25*, *26*, and *27* of the twelve-pole motor, wires run to contacts *25*, *26*, and *27* on the low-tension switch *m*, the fingers of which are connected up by the set of contacts marked *12 pole*, so that fingers *25*, *26*, and *27* are joined to fingers *31*, *32*, and *33*, which are directly connected to the liquid resistance *n*. The controlling apparatus for this liquid resistance is the same as that previously mentioned in connection with the two-speed locomotive. The eight-pole motor *o* is in this case entirely disconnected.

79. Connection of Eight-Pole Motor Alone.—When the eight-pole motor *o*, Fig. 35, is to be run alone, the switch *h* is placed on contacts *4*, *5*, and *6*, thus connecting the stator windings of the eight-pole motor to the mains *1*, *2*, and *3*. The slip-rings *28*, *29*, and *30* are connected by the switch *m*, which is in the position marked *8 pole*, to the terminals *31*, *32*, and *33* of the liquid resistance *n*. The twelve-pole motor is entirely disconnected, the switch *i* being in the off-position.

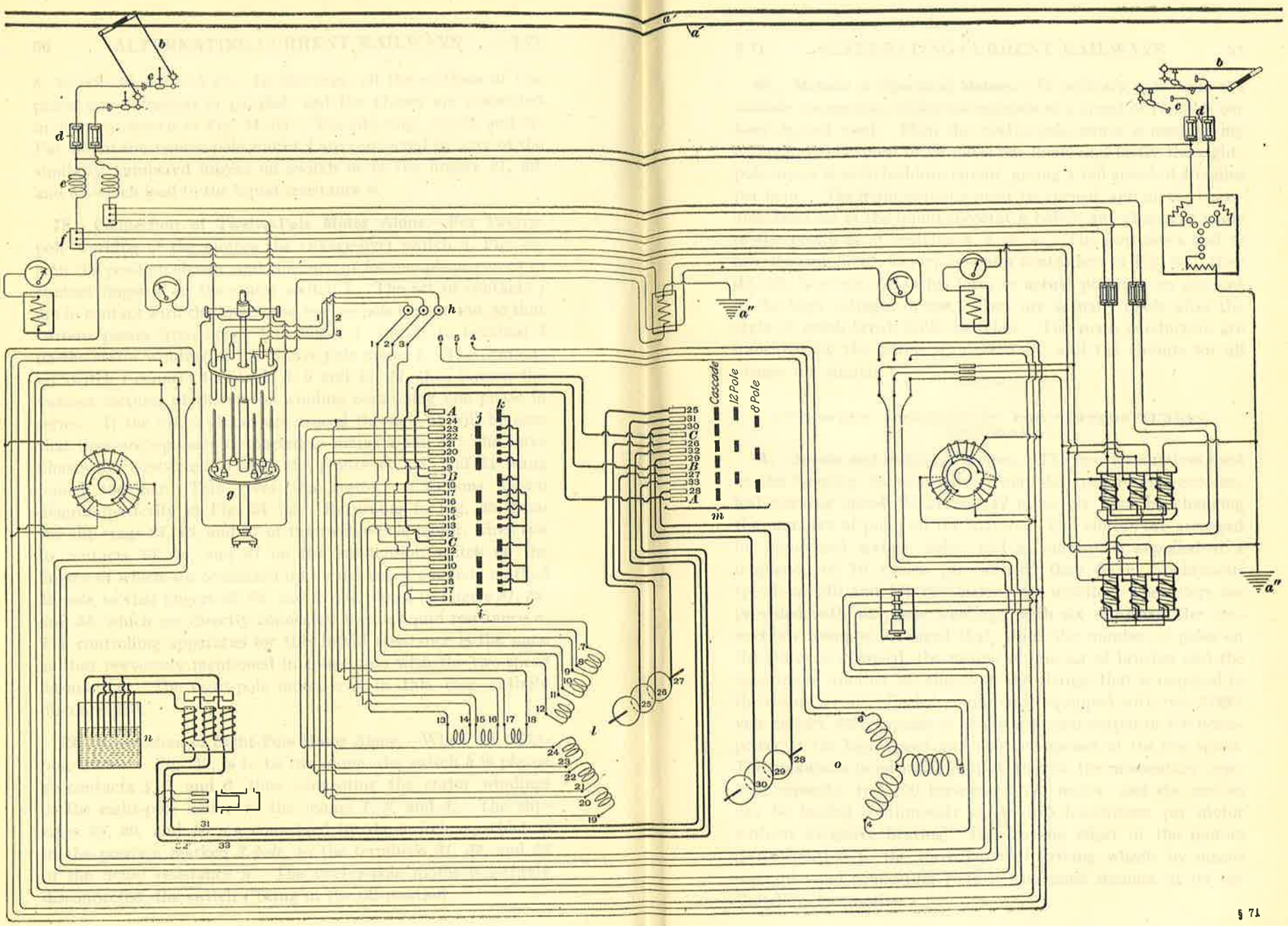
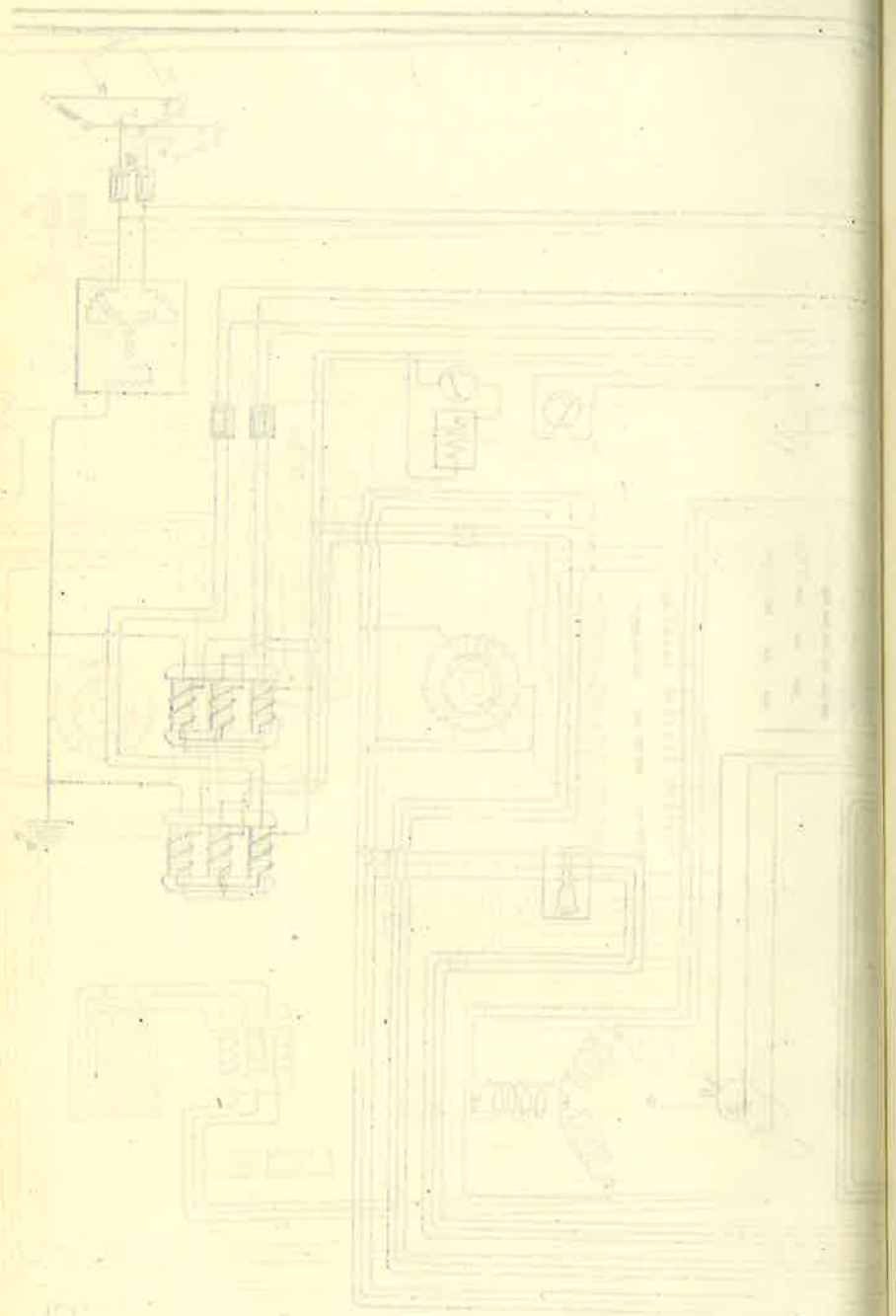


FIG. 85



80. Method of Operating Motors.—In ordinary operation, the cascade connection, which corresponds to a speed of 16 miles per hour, is first used. Then the twelve-pole motor is used, giving a synchronous speed of 26 miles per hour, and lastly the eight-pole motor is switched into circuit, giving a full speed of 40 miles per hour. The main switch g must be opened, and all the resistance inserted in the liquid rheostat n before any change is made in the positions of switches h, i, or m. The switches i and m are, for simplicity, shown as drum controllers in Fig. 35; they do not, however, take this form in actual practice, on account of the high voltages in use. They are actually made after the style of quick-break knife switches. The main conductors are indicated by the letters a, a', and a'', and the circuits for all phases are similar.

TWO-SPEED LOCOMOTIVES FOR SIMPLON TUNNEL RAILWAY

81. Speeds and Rating of Motors.—The first locomotives used on the Simplon Tunnel Railway were designed to give economical working speeds of 21 and 42 miles per hour by changing the numbers of poles on the motors. The motors are arranged for eight and sixteen poles, and as current is supplied at a frequency of 16 cycles per second, they have synchronous speeds of 240 and 120 revolutions per minute. The rotors are provided with six-phase windings, with six slip-rings, the connections being so arranged that, when the number of poles on the stator is changed, the raising of one set of brushes and the lowering of another set effects all the change that is required in the rotor circuit. Each locomotive is equipped with two 3,000-volt motors, each capable of giving a normal output of 450 horsepower at the high speed and 390 horsepower at the low speed. The maximum momentary output, that is, the momentary overload capacity, is 1,150 horsepower per motor, and the motors can be loaded continuously up to 575 horsepower per motor without excessive heating. The turning effort of the motors is transmitted to the three pairs of driving wheels by means of cranks and connecting rods in the same manner as for the Valtellina locomotive.

82. Distribution of Weight.—In the two-speed locomotives, which weigh 62 tons, the weight is carried on three pairs of driving wheels and two pairs of trailers, or pony wheels, as shown in Fig. 36. The load on each pair of trailers is 9 tons,

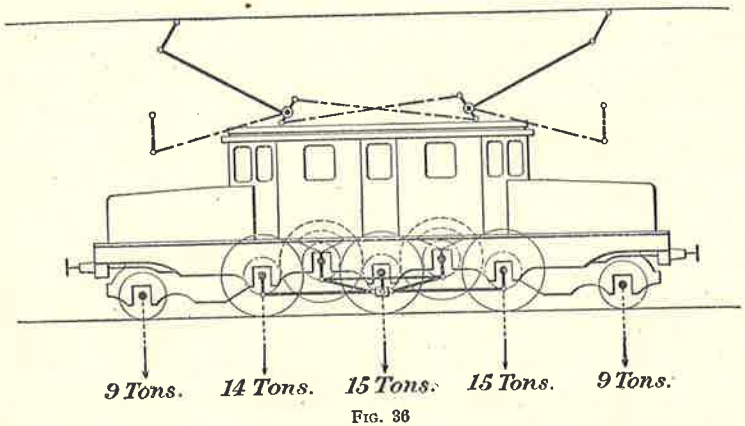


FIG. 36

leaving 44 tons to be carried by the driving wheels. Thus, out of a total of 62 tons, only 44 tons is available to cause the driving wheels to adhere to the track. The pony wheels are of service in guiding the locomotive round curves and in preventing rocking endwise on uneven track.

WIRING DIAGRAM FOR TWO-SPEED LOCOMOTIVE FOR SIMPLON TUNNEL RAILWAY

83. Motor Circuit for Low Speed.—The connections of one of the two-speed Simplon Tunnel locomotives are shown in Fig. 37. From trolley wire *a* the current passes down the bow collector *b*, through the primary of the current transformer *c* to the point *d*, where it divides, part going to the step-down transformer *e*, which supplies the compressor motors and the lighting and heating circuits, and part going to the main motors. The main current passes through the contacts *f* and *g* on the circuit-breaker *A*, which is operated by the pneumatic relay *h*, through contacts *i* and *j* on the reversing switch *B*, the fingers of which are supposed to be on the top row of contacts, through contacts *k* and *l* on the main switch *C* and fuses *m* to the contact

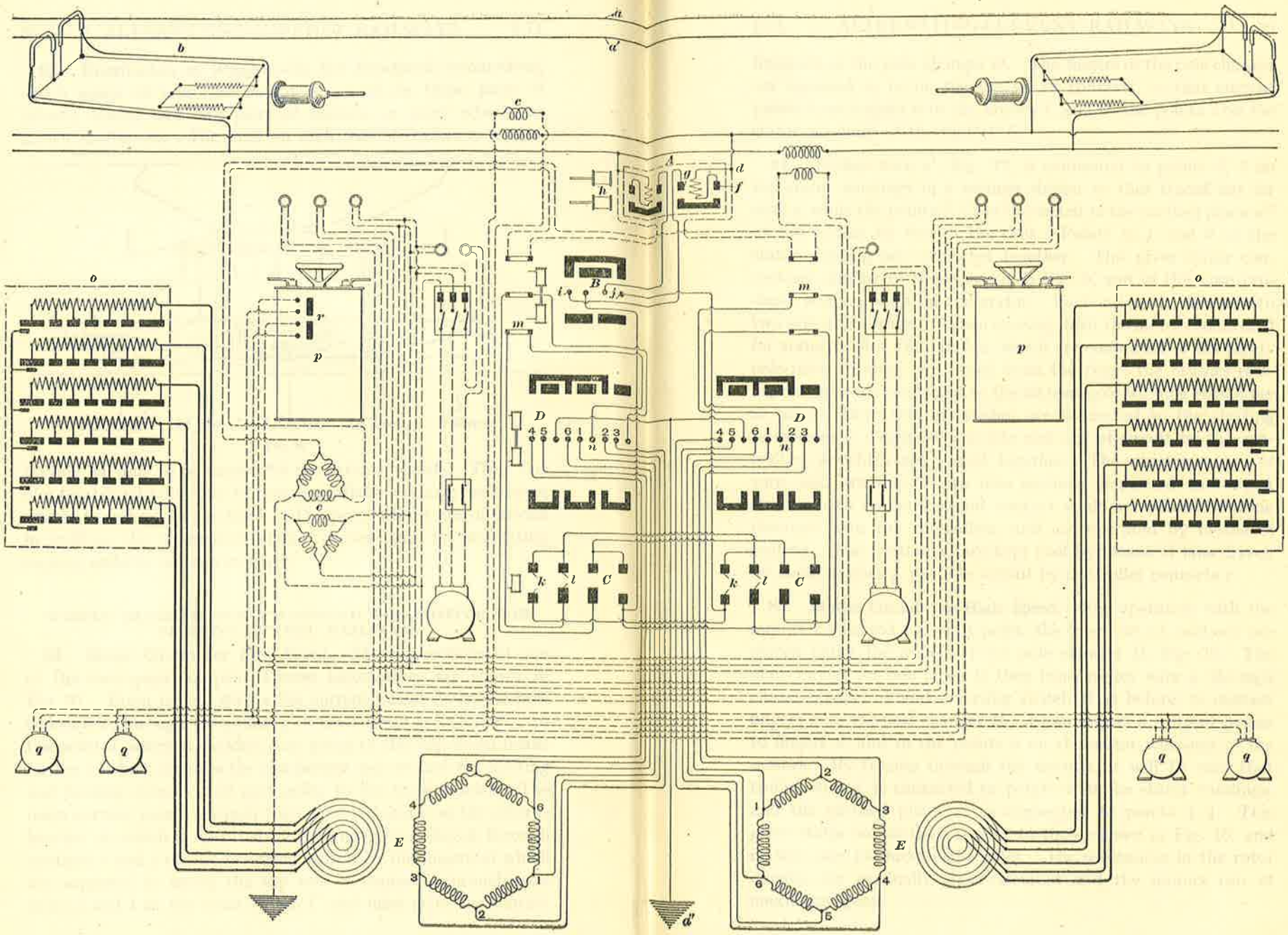
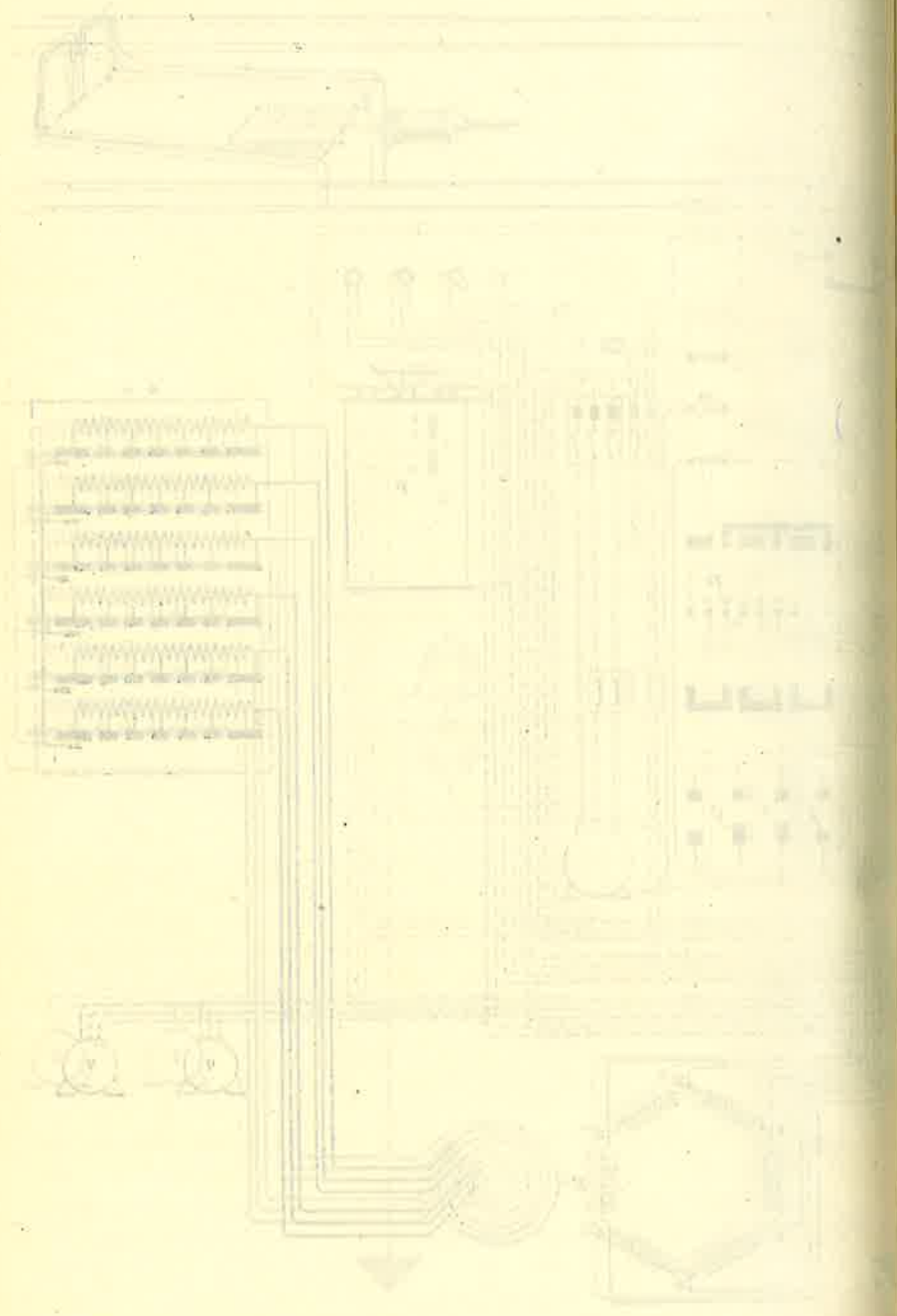


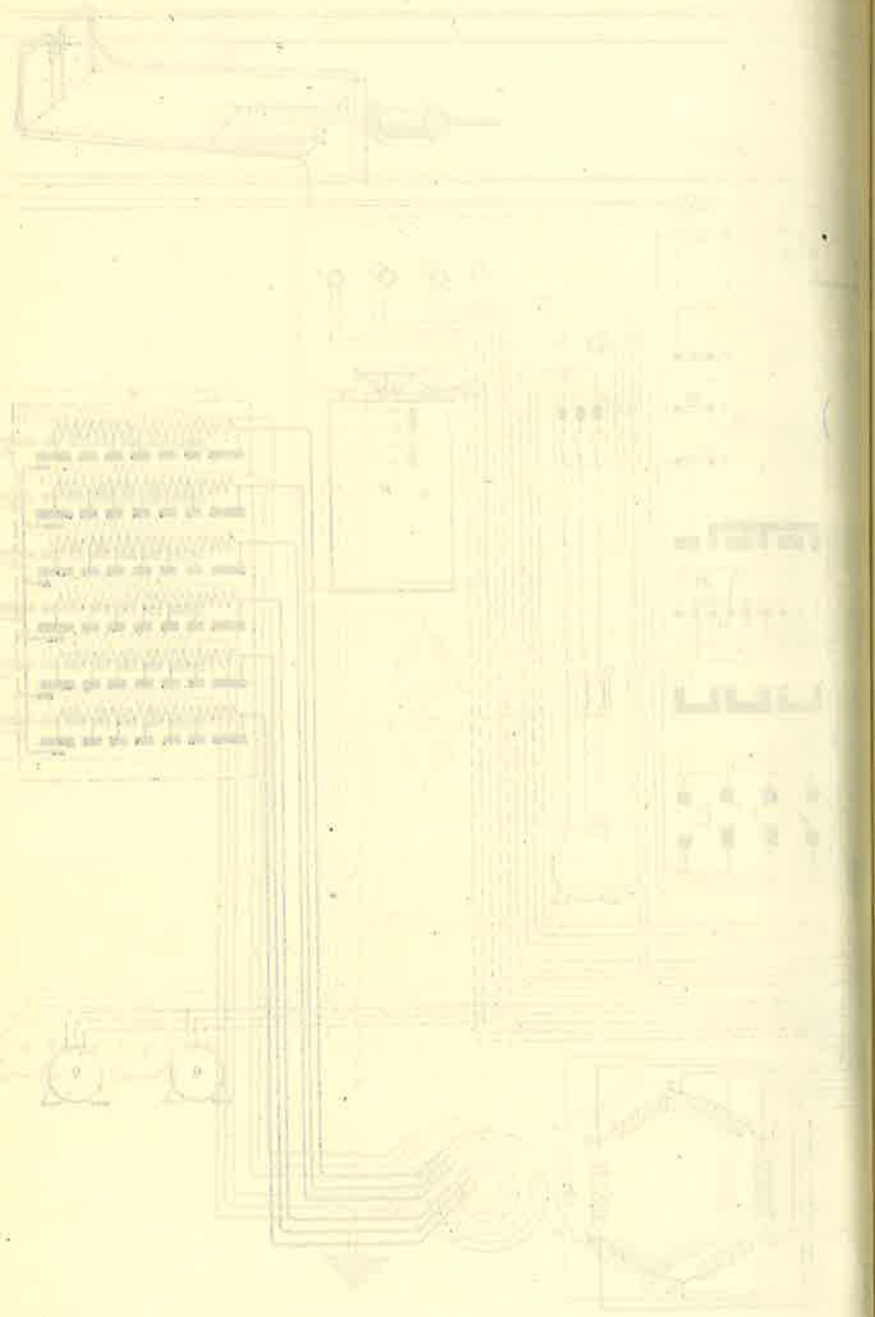
Fig. 37



fingers n on the pole changer D. The fingers of the pole changer are assumed to be on the top set of contacts, so that current passes from fingers n to the fingers *1*, and to the points *1* on the stator windings of the motors E.

84. Trolley wire a', Fig. 37, is connected to points *3*, *3* on the stator windings in a manner similar to that traced out for wire a, while the points *5*, *5* are connected to the earthed phase a'' of the system by way of the rails. Points *2*, *4*, and *6* on the stator winding are connected together. This gives stator connections similar to those shown in Fig. 9, and in this case produces sixteen poles on the stator. Each motor is shown with two sets of slip-rings. When starting with the motors connected for sixteen poles, the brushes, which are connected to the eight-pole rotor winding, are raised from the rings, the brushes resting on the rings connected to the sixteen-pole winding remaining in place. Both sets of brushes are connected to the starting resistances o, which are cut into and out of circuit by the controllers p, which are geared together. The resistances are of wire, and are divided up into sections connected to contact studs; both resistances and contact studs are placed at some distance from the controllers, and are operated by means of gearing. The resistances are kept cool by means of fans driven by small motors q, put into circuit by controller contacts r.

85. Motor Circuit for High Speed.—For operation with the motors connected for eight poles, the lower set of contacts are placed under the fingers of the pole changer D, Fig. 37. The main circuit for one phase is then from trolley wire a, through circuit-breaker A and reversing switch B as before, to contact fingers n on the pole changer D. From fingers n, current passes to fingers *6*, and to the points *6* on the stator windings of the motors. By tracing through the circuits, it will be seen that trolley wire a' is connected to points *2* of the stator windings, and the earthed phase a'' is connected to points *4*, *4*. This gives stator connections similar to those shown in Fig. 10, and in this case produces eight poles. The resistances in the rotor circuits are gradually short-circuited and the motors run at maximum speed.



fingers n on the pole changer D. The fingers of the pole changer are assumed to be on the top set of contacts, so that current passes from fingers n to the fingers *1*, and to the points *1* on the stator windings of the motors E.

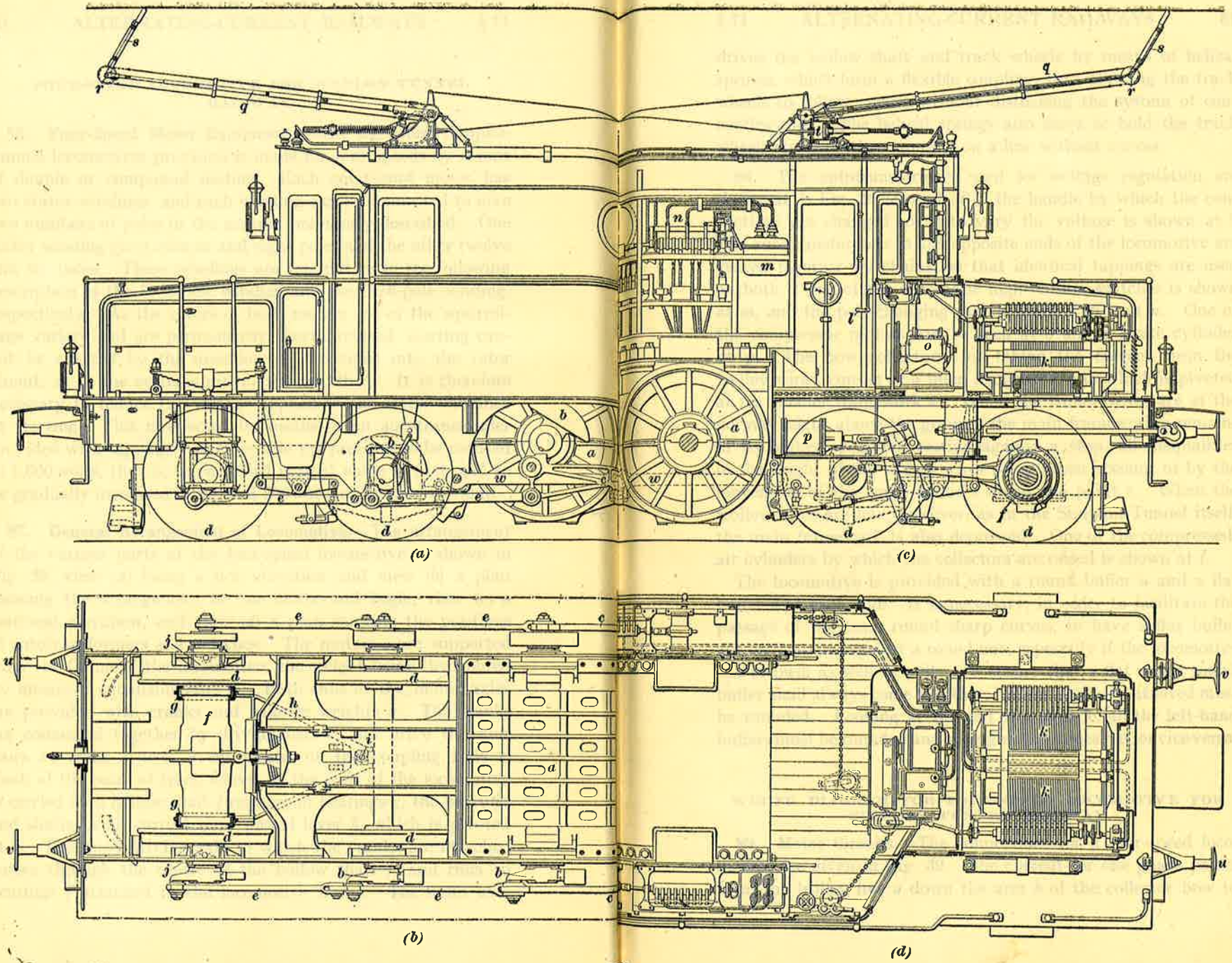
84. Trolley wire a', Fig. 37, is connected to points *3*, *3* on the stator windings in a manner similar to that traced out for wire a, while the points *5*, *5* are connected to the earthed phase a'' of the system by way of the rails. Points *2*, *4*, and *6* on the stator winding are connected together. This gives stator connections similar to those shown in Fig. 9, and in this case produces sixteen poles on the stator. Each motor is shown with two sets of slip-rings. When starting with the motors connected for sixteen poles, the brushes, which are connected to the eight-pole rotor winding, are raised from the rings, the brushes resting on the rings connected to the sixteen-pole winding remaining in place. Both sets of brushes are connected to the starting resistances o, which are cut into and out of circuit by the controllers p, which are geared together. The resistances are of wire, and are divided up into sections connected to contact studs; both resistances and contact studs are placed at some distance from the controllers, and are operated by means of gearing. The resistances are kept cool by means of fans driven by small motors q, put into circuit by controller contacts r.

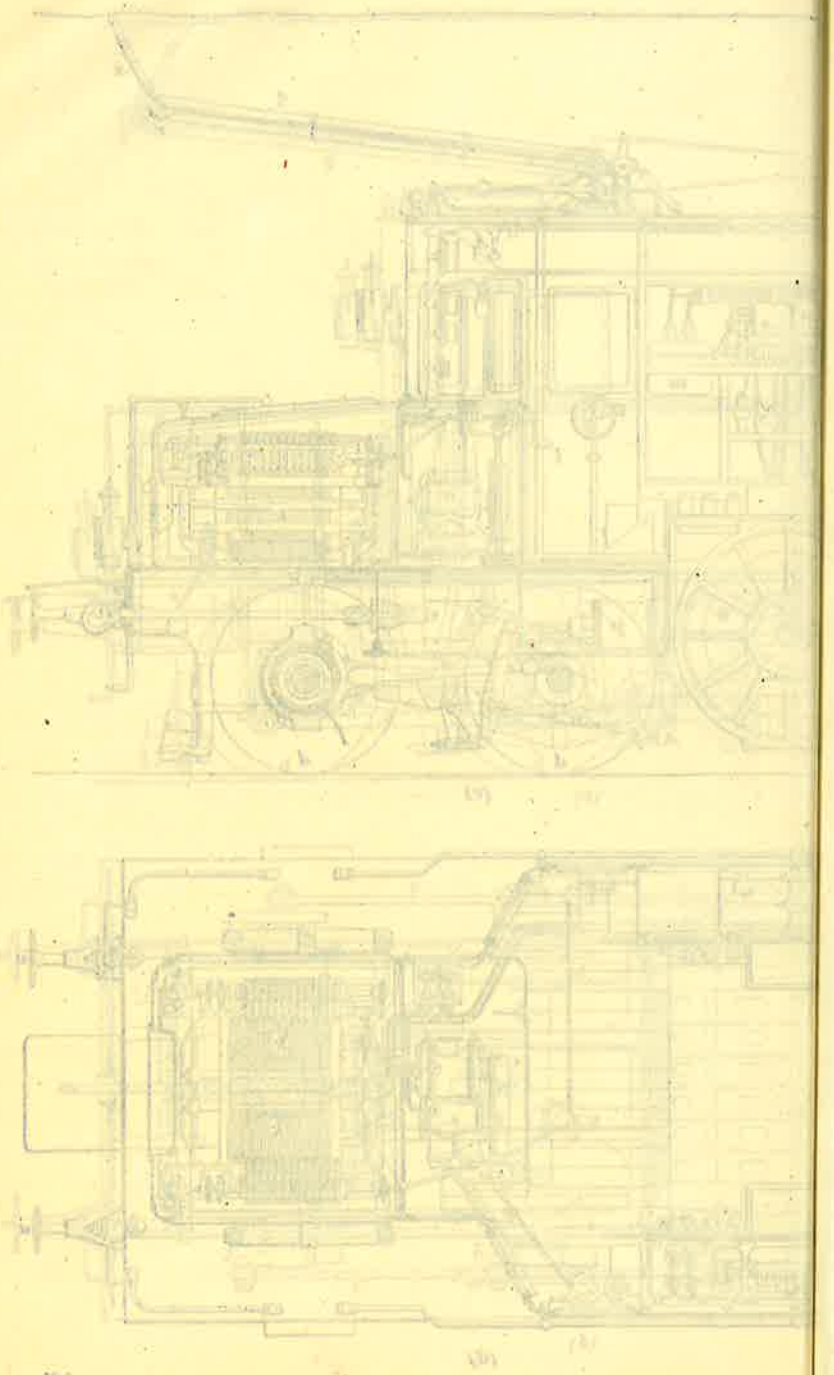
85. Motor Circuit for High Speed.—For operation with the motors connected for eight poles, the lower set of contacts are placed under the fingers of the pole changer D, Fig. 37. The main circuit for one phase is then from trolley wire a, through circuit-breaker A and reversing switch B as before, to contact fingers n on the pole changer D. From fingers n, current passes to fingers *6*, and to the points *6* on the stator windings of the motors. By tracing through the circuits, it will be seen that trolley wire a' is connected to points *2* of the stator windings, and the earthed phase a'' is connected to points *4*, *4*. This gives stator connections similar to those shown in Fig. 10, and in this case produces eight poles. The resistances in the rotor circuits are gradually short-circuited and the motors run at maximum speed.

FOUR-SPEED LOCOMOTIVE FOR SIMPLON TUNNEL RAILWAY

86. Four-Speed Motor Equipment. — On the latest Simplon Tunnel locomotives provision is made for four speeds by means of double or compound motors. Each compound motor has two stator windings, and each winding can be connected to give two numbers of poles in the manner previously described. One stator winding gives sixteen and eight poles and the other twelve and six poles. These windings are referred to in the following description as the 16/8-pole winding and the 12/6-pole winding, respectively. As the rotors of both motors are of the squirrel-cage variety and are permanently short-circuited, starting cannot be effected by the insertion of resistance into the rotor circuit, as in the systems previously described. It is therefore necessary to reduce the voltage applied to the stator windings at starting. This is effected by means of an autotransformer provided with tappings, which enable the pressure to be reduced to 1,000 volts, that is, to one-third normal value at first, and to be gradually increased in steps of 200 volts up to the full value.

87. General Arrangement of Locomotive.—The arrangement of the various parts of the four-speed locomotive is shown in Fig. 38, view (*a*) being a side elevation and view (*b*) a plan showing the arrangement of one motor and bogie, view (*c*) a sectional elevation, and view (*d*) a plan showing the positions of autotransformers and switches. The motors *a* are supported from the frame of the locomotive, the weight being distributed by means of equalizing bars *w*. Both ends of the motor axles are provided with cranks and balance weights *b*. The cranks are connected together by driving bars *c*, and drive the four pairs of track wheels *d* by means of the coupling rods *e*. Each of the pairs of track wheels at the ends of the locomotive is carried on a hollow shaft *f* running in bearings *g*, the bearings and shafts being carried by a forked lever *h*, which is pivoted at *i*. The main driving axle to which the cranks are attached passes through the centre of the hollow shaft *f*, and runs in bearings *j* attached to the locomotive frame. The main axle


(a)
(c)
(b)
(d)



drives the hollow shaft and track wheels by means of helical springs, which form a flexible coupling, thus allowing the track wheels to follow curves without disturbing the system of connecting-rods. The helical springs also serve to hold the track wheels straight when running on a line without curves.

88. The autotransformers used for voltage regulation are shown at *k*, Fig. 38 (*c*) and (*d*); the handle by which the connections are changed so as to vary the voltage is shown at *l*. The autotransformers at the opposite ends of the locomotive are geared together by chains, so that identical tappings are used on both. One of the automatic high-tension switches is shown at *m*, and the pole-changing switch coupled to it at *n*. One of the compressor motors can be seen at *o* and a brake cylinder at *p*. The bow collectors, for taking the current from the trolley wires, consist of a main framework *q* to which is pivoted at *r* a smaller framework *s*. When the trolley wires are at the normal height above the ground, the main framework *q* remains in its highest position, resting against a stop, all inequalities in the height of the trolley wires being taken account of by the movement of the small frame *s* about the point *r*. When the trolley wires are low, however, as in the Simplon Tunnel itself, the main framework is also depressed. One of the compressed-air cylinders by which the collectors are raised is shown at *t*.

The locomotive is provided with a round buffer *u* and a flat buffer *v* at each end. It is necessary, in order to facilitate the passage of the train round sharp curves, to have a flat buffer always pressing against a round one, especially if the locomotive has to push as well as pull. To ensure that a flat and a round buffer shall always come together, buffers similarly situated must be rounded. Looking at the end of a vehicle, all the left-hand buffers must be rounded and the right-hand ones flat, or vice versa.

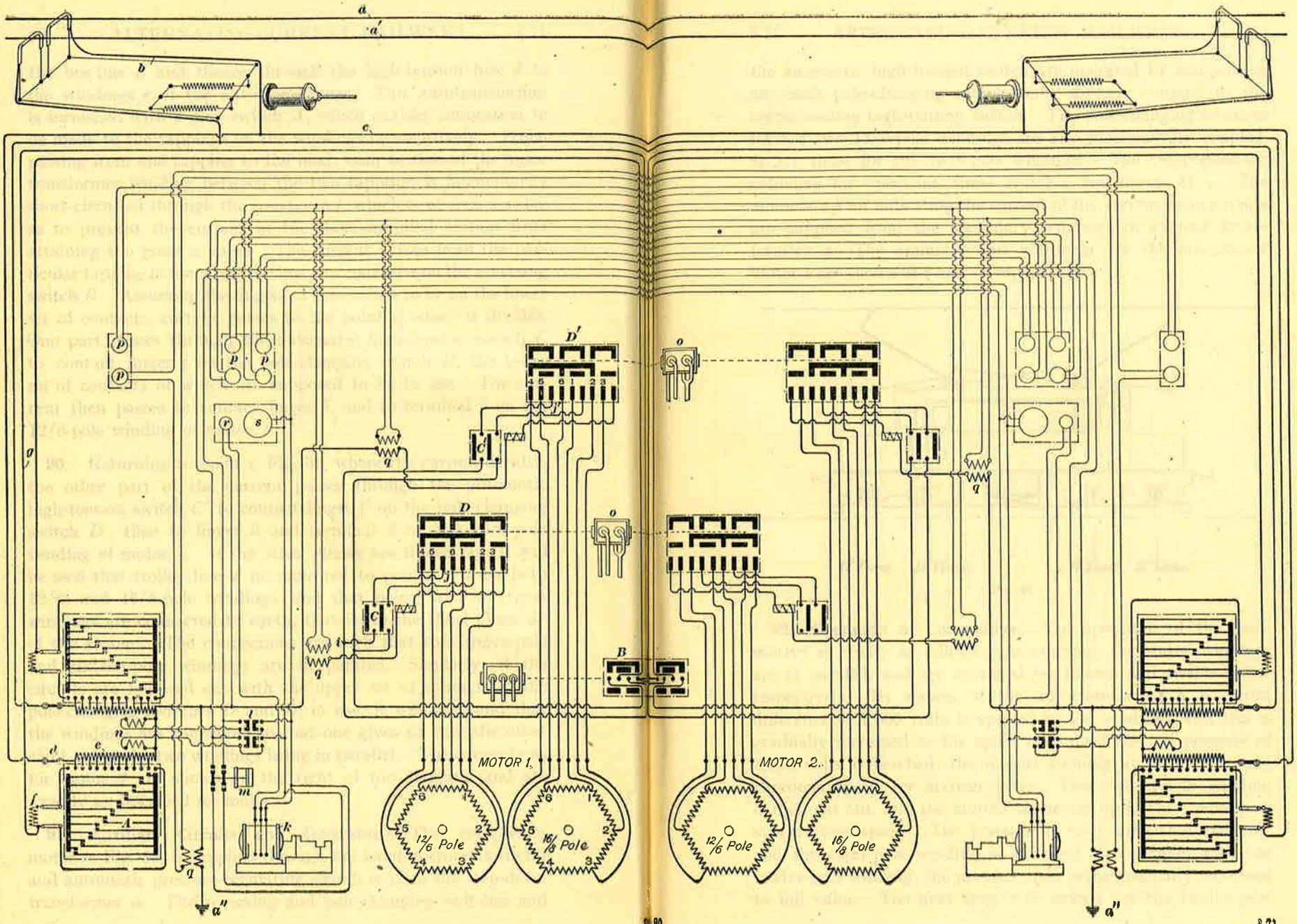
WIRING DIAGRAM FOR FOUR-SPEED LOCOMOTIVE FOR SIMPLON TUNNEL RAILWAY

89. Motor Circuits.—The connections for a four-speed locomotive are given in Fig. 39. The current for one phase passes from the trolley line *a* down the arm *b* of the collector bow to

the bus line *c*, and thence through the high-tension fuse *d* to the windings *e* of the autotransformer. This autotransformer is furnished with a step switch *A*, which enables connection to be made to the tappings on the windings consecutively. When passing from one tapping to the next, each section of the autotransformer winding between the two tappings is momentarily short-circuited through the resistance *f*, which is of such a value as to prevent the current in the short-circuited section from attaining too great a value. The current passes from the particular tapping in use along the line *g* to contact *h* on the reversing switch *B*. Assuming the fingers of this switch to be on the lower set of contacts, current passes to the point *i*, where it divides. One part passes through the automatic high-tension switch *C* to contact finger *j* on the pole-changing switch *D*, the lower set of contacts of which are supposed to be in use. The current then passes to contact finger *5*, and to terminal *5* on the 12/6-pole winding of motor *1*.

90. Returning to point *i*, Fig. 39, where the current divides, the other part of the current passes through the automatic high-tension switch *C'* to contact finger *j'* on the pole-changing switch *D'*, then to finger *5* and terminal *5* on the 16/8-pole winding of motor *1*. If the other phases are traced out, it will be seen that trolley line *a'* is connected to points *1*, *1* on both 12/6- and 16/8-pole windings, and that points *3*, *3* on these windings are connected to earth, that is, to the third phase *a''* of the system. The connections are such that the twelve-pole and sixteen-pole windings are in parallel. Similarly, if the circuits are followed out with the upper set of contacts in the pole-changing switches *D* and *D'* in use, it will be found that the windings are connected so that one gives six and the other eight poles, the two windings being in parallel. The connections for motor *2* are shown on the right of the diagram, and are exactly as described for motor *1*.

91. Auxiliary Circuits and Apparatus. — The compressor motor *k*, Fig. 39, is supplied through the hand-operated switch *l* and automatic pressure-regulating switch *m* from the step-down transformer *n*. The reversing and pole-changing switches and


a
a'
b
c
D'
D
B
o
p
r
s
q
g
d
e
f
n
m
k
A
MOTOR 1.
MOTOR 2.
12/6 Pole
16/8 Pole
12/6 Pole
16/8 Pole
a''
a''

the automatic high-tension switch are operated by compressed air, each pole-changing switch being directly coupled to the corresponding high-tension switch. The pole-changing switches for the two 12/6-pole windings are also mechanically coupled, as are those for the 16/8-pole windings. The compressed-air cylinders for operating these switches are shown at *o*. The ammeters *p* for indicating the current in the various main circuits are supplied from the secondary windings of current transformers *q*. The ammeter and voltmeter for the compressor motor *k* are shown at *r* and *s*, respectively

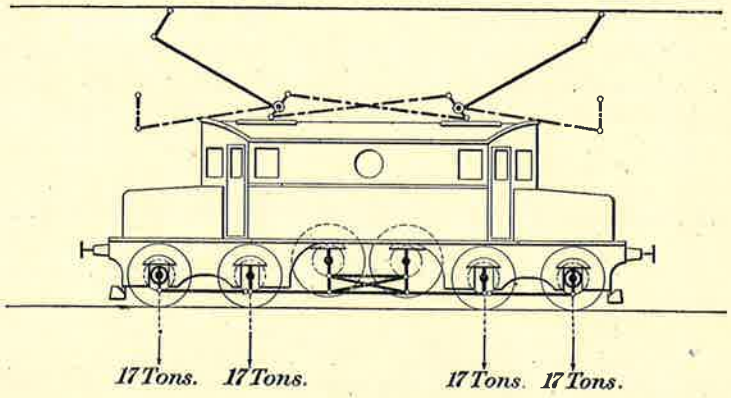


FIG. 40

92. Operation of Locomotive.—The operation of the locomotive is briefly as follows: At starting, the stator windings are in parallel, and are arranged for sixteen and twelve poles, respectively. By means of the autotransformer a potential difference of 1,000 volts is applied to the windings, and this is gradually increased as the speed rises until the full pressure of 3,000 volts is reached, the motors running at about the synchronous speed for sixteen poles. The sixteen-pole winding is then cut out, and the motors accelerate up to the twelve-pole synchronous speed. The pressure is next somewhat reduced, and the eight-pole winding is switched into parallel with the twelve-pole winding, the pressure then being gradually increased to full value. The next step is to switch out the twelve-pole

winding, thus causing the speed to rise to the eight-pole synchronous value. To attain the highest speed the pressure is again reduced, and the six-pole winding is placed in parallel with the eight-pole winding, the pressure is raised to full value, and finally the eight-pole winding is switched out.

93. Disposition of Weight.—There is a marked difference between the two-speed Simplon locomotives previously described and the four-speed ones at present under consideration. In the four-speed locomotives the total weight of 68 tons is equally divided, by means of an equalizing system of suspension, among four pairs of driving wheels, as shown in Fig. 40, each pair carrying 17 tons. The whole weight of 68 tons is thus available in producing adhesion. This is a great advantage where heavy gradients must be ascended.

OVERHEAD CONSTRUCTION FOR THREE-PHASE RAILWAYS

VALTELLINA RAILWAY

94. Usual Arrangement of Conductors.—It has already been stated that on most three-phase railway systems the rails are used as one conductor, and therefore only two overhead lines are required. This arrangement has the advantage of simplicity, but possesses a slight drawback in that the use of the rail makes the system unbalanced. Especially is this the case at high frequencies, because the impedance of the rails has a greater value than that of the overhead lines. When the rails are used as one conductor and two trolley wires per track are employed, the method of suspension for moderate voltages is almost identical with the span-wire construction used for direct-current tramway work, though the insulators used are heavier.

95. Method of Supporting Transmission and Trolley Wires. On the Valtellina Railway electrical energy is generated at 20,000 volts and transmitted by an overhead three-phase line to

transformer substations, from which energy at 3,000 volts is supplied to the working conductors. Where possible, the lines used to transmit the energy from the central station are carried on an extension of the poles which carry the trolley wire. When the track passes through a tunnel the transmission lines are carried on separate poles outside the tunnel. The contact wires are carried above the rails at a height of nearly 20 feet, which is reduced to 15·75 feet in tunnels. The construction, which is adopted for a single track on curves of less than 1,125 yards radius, is shown in Fig. 41. The supporting poles *a*, *a′* are connected by a cross-beam *b*. The insulators *c* supporting the 20,000-volt transmission line are carried by iron supports on an extension of the pole *a′*. The trolley wires *d* are supported from insulators *e* made of a strong insulating compound known as *ambroin*. These insulators are attached to steel span wires *f*, which are fastened to porcelain insulators *g* bolted to the poles *a*, *a′*. The outline of the rolling stock used on the line is shown dotted at *h*.

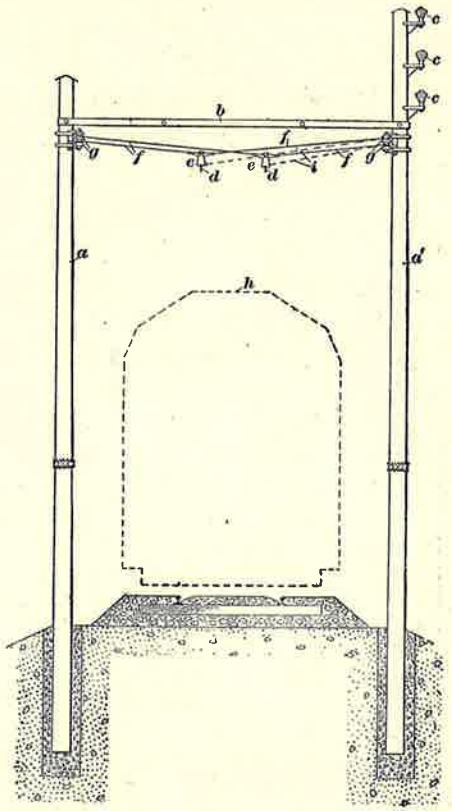


FIG. 41

96. Where there are no curves, or where the radius of curvature is greater than 1,125 yards, the trolley wires are supported

from brackets carried by single poles, as shown for a double track in Fig. 42. The various parts are lettered as in Fig. 41.

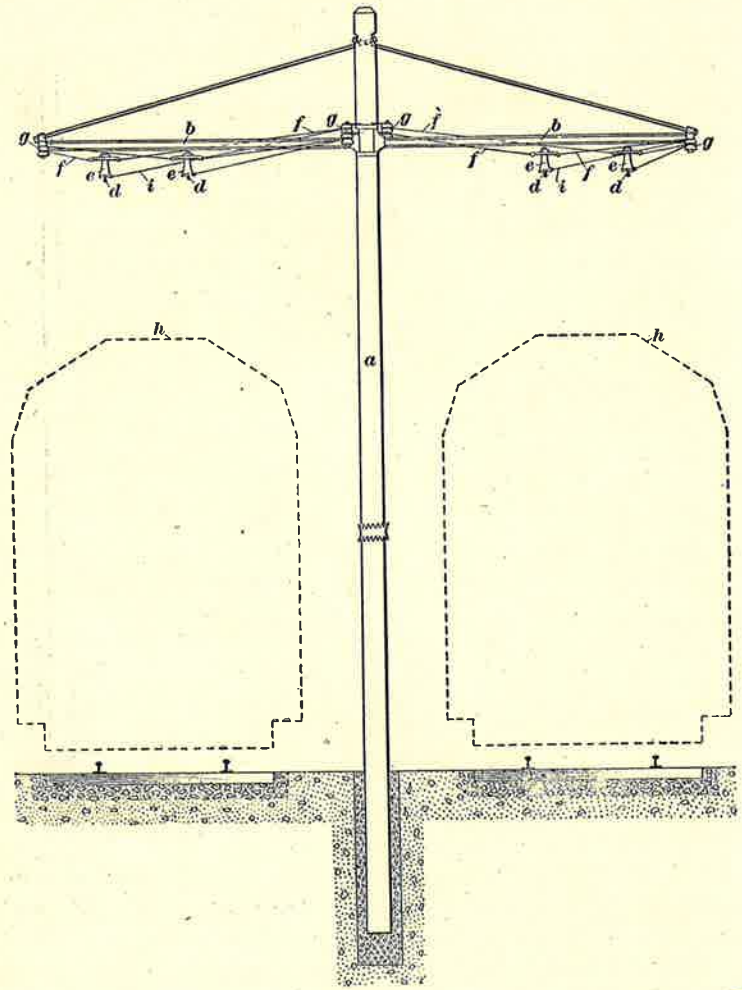


FIG. 42

The 20,000-volt transmission lines are carried on separate poles. In all cases the poles are set in concrete.

97. Trolley Insulators.—The construction of the trolley insulator *e*, Fig. 42, is shown in detail in Fig. 43 (*a*), (*b*), and (*c*). The iron bolt *a* is almost completely covered by the ambroin insulating material *b* which is moulded round it. This ambroin-covered bolt is inserted in an iron petticoat *c*, which is provided with grooved arms *d*. To the bottom of bolt *a* is attached a clip *e* consisting of two cheeks of galvanized iron, between which the

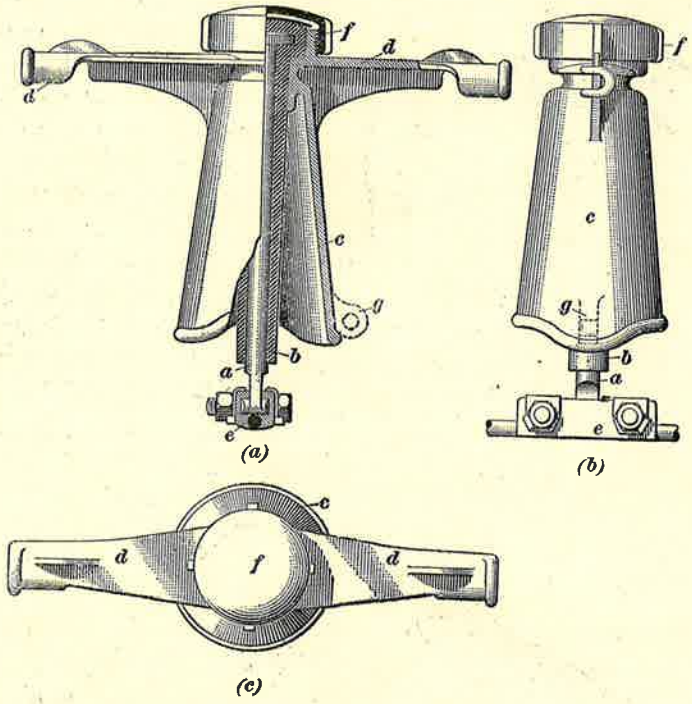


FIG. 43

trolley wire is clamped. The top of the ambroin-covered bolt is held in place and protected from the weather by the cap *f*, which screws on to the iron frame. The span wire from which the insulator is suspended passes along the groove in the arms *d* and round the top of the petticoat *c*, as in the ordinary hanger for direct-current tramway trolley wires. On curves, the base of the iron petticoat is provided with an eye, as shown dotted

at g, to which is fastened a wire which ties the insulator to the post. This is necessary in order to balance the side pull of the trolley wire. The tie-wires are indicated by the lines i in Figs. 41 and 42.

98. Transmission and Span-Wire Insulators.—The 20,000-volt lines that supply energy to the substations are carried on porcelain insulators made in three parts, as shown at a, b, and c, Fig. 44 (a). The parts of the insulator are held together by means of cement, and a screw thread is provided on section b for the insulator pin.

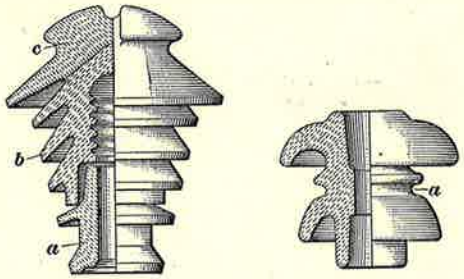


FIG. 44

The span wires which support the working conductor are fastened to porcelain insulators of the form shown in Fig. 44 (b). The span wire is tied round the insulator in the groove a, and a bolt through the hole supports the insulator.

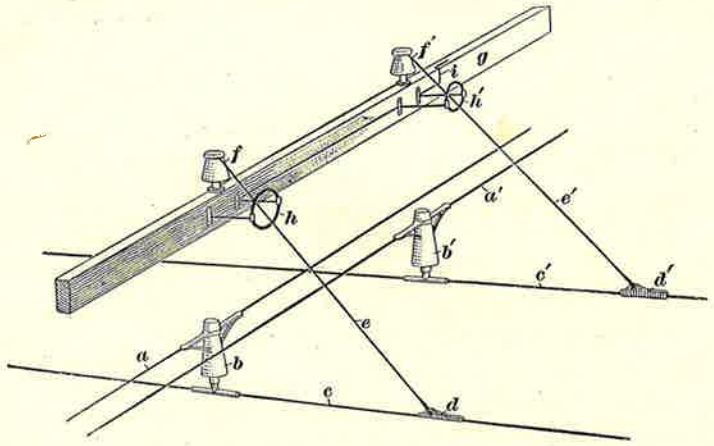


FIG. 45

99. Earthing Device.—On account of the high voltage used on the trolley wires, it becomes necessary to provide some device

for instantly earthing the trolley wire if either that or the span wire should break. The method adopted at level crossings on the Valtellina Railway is shown in Fig. 45. The span wires are shown at a, a', the insulators at b, b', and the trolley wires at c, c'. The trolley wires have attached to them at the points d and d' two short lengths of wire e, e', which terminate at the insulators f, f' on the cross-bar g. These wires pass through metal loops h, h' which are connected to the wire i, the other end of which is earthed. If either of the span or trolley wires should break, the wire e or e' makes contact with one of the metal loops h, h' and earths the trolley wire to which it is connected.

OVERHEAD CONSTRUCTION ON SIMPLON TUNNEL RAILWAY

100. The overhead construction in the Simplon Tunnel is another example of the use of span wires. On account of the limited space available, a compact and strong construction was necessary, and exceptional care had to be taken with the insulation on account of the great heat and dampness of the tunnel. The construction adopted is shown in Fig. 46, each overhead conductor being composed of two wires in parallel. The trolley

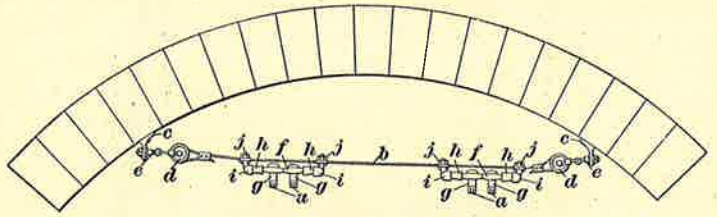


FIG. 46

wires a are supported from a copper-plated steel span wire b, which is stretched between insulators d fastened by means of eyebolts e to gunmetal studs c. The studs are grouted into the roof of the tunnel. As only one span wire is used, each trolley wire is doubly insulated from the span wire in order to secure effective insulation between the phases. The trolley wire is held in a clip, or ear, which is fixed in a gunmetal cross-bar f

by means of ebonite-insulated bolts *g*. Porcelain insulators *h* are screwed on at each end of the cross-bar, a layer of hemp and asbestos being inserted between the screw and the porcelain. The insulators *h* are screwed to gunmetal caps *i*, a layer of rubber being placed between the two, and the caps are fastened to the span wire *b* by gunmetal clamps *j*. The design of these insulators makes quick repairs possible, as each part is separately replaceable. Each insulator is capable of withstanding a pressure of 40,000 volts, which is more than sufficient for a working pressure of 3,300 volts, even under the unfavourable conditions prevailing in the tunnel. Tests have shown that the leakage from the trolley wires is very small.

101. The overhead work outside the tunnel is supported by light structures of steel tube, as shown in Fig. 47. The support *a*

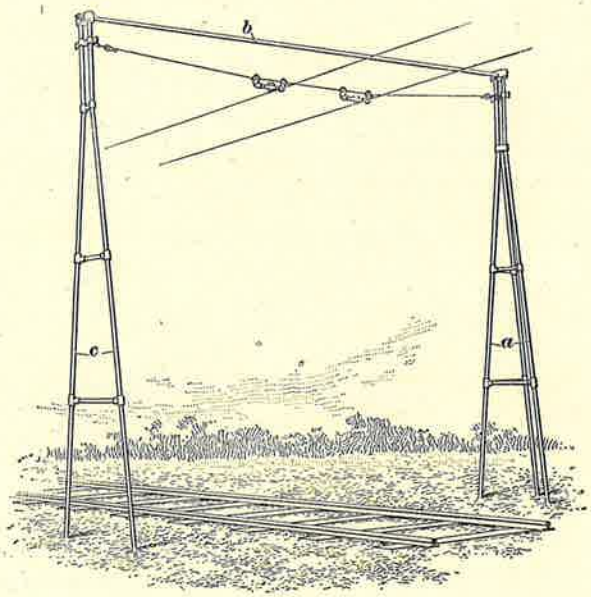


FIG. 47

on one side of the track is a tripod, and is connected by the tube *b* with a two-legged support *c*. This gives an exceedingly light

and compact structure, which is very rigid and strong. Where a large number of tracks are to be spanned, tripods are used at each side, and are connected by horizontal tubes to two-legged supports between each track.

102. Joints and Crossings.—The arrangement of two overhead wires necessary for three-phase working leads to difficulties at places where two tracks join or cross. On railways where junctions are numerous, this consideration is important, and causes the three-phase system to compare unfavourably with other systems. At large stations where complicated junctions occur, it is doubtful as yet if the advantages of the three-phase as compared with other systems would outweigh this drawback, but for less exacting cases and for main line work, there is no doubt that the adoption of the three-phase system is well worth consideration.

In many respects the difficulties experienced in arranging the overhead lines at junctions, crossings, etc., are similar to those encountered on direct-current railways employing third and fourth rails, somewhat modified, however, by two facts: first, that the overhead lines do not follow the line of the track exactly, as is the case with conductor rails, and, second, that it is desirable for mechanical reasons to keep overhead wires continuous, whereas conductor rails must be discontinuous where they cross the running rails. The reason for keeping the overhead wire continuous is that it is undesirable to let the bow travel freely in the air. If there were a gap in the overhead line, the wires at both ends of the gap would have to be terminated and inclined in such a way that there would be no difficulty in the collector coming on to the wire again, even at high speeds. Continuity is obtained by the use of a dead wire, which is insulated from the live wire by strips of impregnated wood. It must, of course, be so arranged that no bow can touch two live wires of different phases, and that no dead wire can short-circuit two bows of opposite phases. It is further desirable that a car shall be able to start, if required, from a junction, and therefore the length of any dead section must be less than the distance between the collectors at the two ends of the locomotive or coach.